Impairment Aware Routing with Service Differentiation in Heterogeneous WDM Networks

Amornrat Jirattigalachote[*a], Lena Wosinska[a], Paolo Monti[a], Kostas Katrinis[b], Anna Tzanakaki[b]

[a]Royal Institute of Technology KTH, School of Information and Communication Technology, Isafjordsgatan 22, Electrum 229, 164 40 Kista, Sweden
[b]Athens Information Technology (AIT), 19.5 Markopoulou Av., P.O. Box 68, 19002 Peania, Greece

ABSTRACT

In transparent Wavelength Division Multiplexing (WDM) networks, the signal is transported from source to destination in the optical domain through all-optical channels, or lightpaths. A lightpath may traverse several fiber segments and optical components that in general degrade the optical signal. This effect introduces the need for considering physical layer impairments during the connection-provisioning phase. Physical layer impairments can be divided into *linear* and *non-linear*. Both types of impairments are highly dependent on the fiber characteristics, which in turn are sensitive to length, temperature and age. A close look at the fiber infrastructure of today's network operators reveals a situation where old and newly deployed fibers coexist in the network. This heterogeneous fiber plant presents a challenge. A tradeoff should be found between the QoS requirements of connection requests and the use of the available (old and new) network resources. This calls for a provisioning mechanism able to adapt to the various fiber composition scenarios.

In parallel, given the need for *service differentiation*, the authors recently proposed an Impairment Constraint Based Routing (ICBR) algorithm, referred to as ICBR-Diff, supporting differentiation of services at the BER (Bit Error Rate) level in a network with a homogeneous fiber infrastructure. In this paper the ICBR-Diff algorithm is extended to heterogeneous network; particularly, it is evaluated in WDM networks with fiber links having varying Polarization Mode Dispersion characteristics, i.e., with old and new fiber coexisting. Simulation results show that the ICBR-Diff algorithm exhibits high adaptability in a heterogeneous fiber composition scenario. This translates into improved performance in terms of blocking probability, when compared to traditional impairment aware routing algorithms.

1. INTRODUCTION

Transparent WDM networks constitute a promising solution to cater for the rapid growing of bandwidth demand in next generation networks. In such networks the signal is transported from source to destination in the optical domain through all-optical channels (also referred to as *lightpaths*[1]), without the need for intermediate optoelectronic conversion. In this way transparency to bit rate, signal format, and protocols can be obtained. Moreover, the number of O/E/O converters (i.e. transmitters and receivers) can be lowered causing a significant reduction in cost.

However, due to lack of signal regeneration functionality in transparent optical networks the signal quality may be degraded due to physical layer impairments that can accumulate along the path. This effect introduces the need for considering physical layer impairments during the connection-provisioning phase, i.e., the need to solve the so-called Impairment Aware Routing and Wavelength Assignment (IA-RWA) problem. The objective of the IA-RWA problem is not only to minimize the network blocking probability (i.e., accommodate as many connection requests as possible by reserving, for each one of them, the minimum number of network resources) but also to guarantee the required quality of transmission level, e.g., measured in terms of bit error rate (BER), for each connection. Physical layer impairments can be divided into *linear* and *non-linear*. Linear impairments do not depend on the signal power and affect each channel

[*] amornrat@kth.se; phone: +46 8 790-4083, fax: +46 8 790-4090, web: http://www.ict.kth.se/MAP/FMI/Negonet/

Network Architectures, Management, and Applications VII, edited by Ken-ichi Sato, Yuefeng Ji, Lena Wosinska, Jing Wu, Proc. of SPIE-OSA-IEEE Asia Communications and Photonics, SPIE Vol. 7633, 763307 · © 2009 SPIE-OSA-IEEE · CCC code: 0277-786X/09/$18

individually. A list of the most important linear impairments includes: Amplified Spontaneous Emission (ASE) noise, Group Velocity Dispersion (GVD) and Polarization Mode Dispersion (PMD). ASE is due to optical amplification, whereby optical amplifiers (e.g., EDFAs) degrade the optical signal to noise ratio (OSNR) of the transmitted signal. GVD causes a pulse broadening effect and is the result of different spectral components traveling at different velocities. This, in turn, affects the receiver performance. PMD causes optical power variation and signal distortion. This is caused by the fiber birefringence due to which one of the two orthogonally polarized modes travels slower than the other. Non-linear impairments on the other hand, both impact each channel individually and affect other channels[2][3]. They manifest at higher bit rates (i.e., 10 Gb/s and above) and/or at higher transmitted powers. A list of the most important non-linear impairments includes: Self Phase Modulation (SPM), Cross Phase Modulation (XPM) and Four Wave Mixing (FWM). They result from the dependence of the fiber refractive index on the intensity of the applied electric field. This, in turn, produces chirping for the transmitted pulses[4]. In summary both linear and non-linear impairments are highly dependent on the fiber characteristics which in turn are sensitive to length temperature and age.

The fiber infrastructure of today's network operators reveals a situation where old and newly deployed fibers are coexisting. This situation is the result of an evolution driven mostly by two reasons. First, network operators had to face the challenge of keeping up with the growing demand for low cost transmission bandwidth. This lead (and it still leading) to an expansion of the core networks with denser WDM transmission systems (e.g., up to 80 channels) operating at higher line rates (e.g., from to 2.5 Gb/s to 10 Gb/s and 40 Gb/s). Second network operators had to replace fibers that have been operative since the 1980s[5]. This heterogeneous fiber plant presents challenges, since new and old fibers differ in physical characteristics and may or may not be able to accommodate demanding traffic (i.e., in terms of BER requirements) at high transmission rates. A tradeoff should be found, during the provisioning phase, between the QoS requirements of the connection requests and the use of the available (old and new) network resources. This calls for provisioning mechanism able to adapt to the various fiber composition scenario, while satisfying service requirements.

The latter requirement is not taken into consideration by conventional Impairment Constraint Based Routing (ICBR) algorithms[6][7] that have been proposed to solve the IA-RWA problem. Usually they are referred to as Impairment-Aware Best-Path (IABP) routing algorithms, since they always assign each connection the least impaired path, regardless of the connection signal quality requirement. In other words, they support only a single quality of transmission threshold, uniformly to all connection requests (i.e., the lowest BER value, in case of IABP routing). As a consequence, such single-threshold approaches may unnecessarily block connection requests that otherwise may sustain a higher BER threshold (i.e., may use worse performing fiber). On the other hand, for those connection requests that are accepted, a single-threshold scheme may overprovision network resources (i.e., traffic with low BER threshold is assign to high performing fibers), with a detrimental effect on the overall blocking probability. To overcome these deficiencies, , the authors recently proposed an ICBR algorithm, referred to as ICBR-Diff[8], supporting differentiation of services at the BER level in a network with a homogeneous fiber infrastructure. In the proposed approach, various BER thresholds are considered for accepting/blocking connection requests in the connection-provisioning phase, depending on the QoS requirements of the connection requests.

This paper extends our previous work by evaluating the ICBR-Diff algorithm in WDM networks with fiber links having varying PMD characteristics. This is to reflect the realistic scenario, whereby new and old fibers coexist in the same network, thus calling for the need to account for the heterogeneity in fiber characteristics during connection provisioning. Simulation results, on the Pan-European test network topology, show that the ICBR-Diff algorithm exhibits high adaptability in a heterogeneous fiber composition scenario: by adapting the lightpath provisioning mechanism to the BER requirements of incoming connection requests, ICBR-Diff manages to reserve the best performing links for future use, when new and more demanding connection requests, in terms of BER, are to be set up. In turn, this translates into improved performance in terms of blocking probability when compared to traditional impairment aware routing algorithms applied to the same scenario.

2. HETEROGENEOUS NETWORK MODEL AND ICBR-DIFF ALGORITHM

In this section, we first present definitions and assumptions for the network scenario under consideration. Then a mathematical model for physical layer impairments is introduced. This model is then used to create a fiber heterogeneous network plan that is handled by our ICBR algorithm with service differentiation based on requested BER level (ICBR-Diff).

2.1 Definitions

In this paper, we assume that connection requests demand bandwidth at wavelength granularity, i.e. each request can demand integral multiples of a wavelength. Also, wavelength conversion capability is not available, i.e. the wavelength continuity constraint has to be considered. Furthermore, our experimental model assumes random and dynamic incoming connection requests that are sequentially served without prior knowledge of future incoming connection requests. More precisely, incoming connection requests follow a Poisson distribution, while source/destination pairs are randomly chosen with equal probability (uniform distribution) among all network nodes. Connection holding time is exponentially distributed.

As previously mentioned, the ICBR-diff algorithm supports differentiation of services. We consider two classes of service, thus dividing connection requests into two distinct classes with regards to their signal quality requirements, i.e. Class-1 requests requiring higher signal quality and Class-2 requests that can tolerate higher signal quality degradation than Class-1. Throughout our simulations, Class-1 connection requests require BER less than 10^{-15} and Class-2 connection requests require BER less than 10^{-9}. This assumption is based on IP traffic measurements of today's Internet [11][12]. These measurements show that peer-to-peer and World Wide Web (WWW) traffic (corresponding to our Class-2 type of traffic) is increasingly dominating bandwidth utilization, while streaming media traffic (corresponding to our Class-1 type of traffic) accounts for a small part of the total bandwidth utilization. According to our ICBR-Diff algorithm, a Class-1 connection request is blocked, if there is no lightpath connecting the two endpoints of the connection request that exhibits BER less than 10^{-15}; whereas a connection request of Class-2 is blocked if there is no lightpath with BER less than 10^{-9}.

2.2 Creating a fiber heterogeneous network scenario

In this work, the effect of physical layer impairments is quantified by using the quality factor Q, following the work presented by G. Markidis et al.[6]. Furthermore, the power penalty due to Polarization Mode Dispersion (PMD) proposed by C.D. Cantrel[9] is used to extend the Q-penalty factor presented by G. Markidis[6], so that the effect of PMD is accounted for. The considered Q-penalty factor includes both linear and nonlinear physical impairments, namely Amplified Spontaneous Emission (ASE) noise, Four Wave Mixing (FWM), the combined Self Phase Modulation/Group Velocity Dispersion (SPM/GVD) and optical filtering effects, Cross Phase Modulation (XPM), and PMD. ASE, FWM and XPM are calculated assuming that they follow a Gaussian distribution. For the combined SPM/GVD and optical filtering effects, they are quantified through an eye closure penalty metric calculated on the most degraded bit-pattern. The Q-penalty factor on the *k*-link is given according to the equation (1),

$$Q_{penalty,k} = \frac{pen_{PMD,k} \cdot \sqrt{\sigma^2_{ASE,k} + \sigma^2_{FWM,k} + \sigma^2_{XPM,k}}}{pen_{eye,k}} \tag{1}$$

where $pen_{PMD,k}$ is the power penalty due to PMD, and $pen_{eye,k}$ is the relative eye closure attributed to SPM/GVD and optical filtering effects, calculated semi-analytically through single channel simulations. Furthermore, $\sigma^2_{ASE,k}$ is the electrical variance of ASE noise, while $\sigma^2_{FWM,k}$ and $\sigma^2_{XPM,k}$ are the electrical variance of FWM and XPM induced degradation respectively.

The Q-penalty factor expressed by equation (1) is used to recreate a fiber heterogeneous network scenario, in the following way. We assume to have two types of fiber in our network (old fibers and new fibers), each one with different PMD parameters (and consequently different values of $pen_{PMD,k}$). The first type, representing an old fiber, is assumed to have PMD equal to 0.5 ps/√km. The second type, representing a new fiber, is characterized by PMD equal to 0.1 ps/√km.

2.3 ICBR-Diff algorithm

The flowchart of the ICBR-Diff algorithm, that handles a fiber heterogeneous scenario, is presented in Figure 1. The algorithm starts with collecting the network topology information in the initialization phase (number of nodes and links, link lengths and capacities); also the physical parameters required for the calculation of the Q-penalty factor of each link are determined. In order to study the effect of fiber heterogeneity, each fiber link is randomly assigned one of the two fiber types considered (new or old) during the initialization phase.

In our study, two routing algorithms are considered *(i)* shortest path routing, with link physical distance corresponding to link cost, and *(ii)* impairment constraint routing, where the Q-penalty factor is used as link cost. In addition, the cost of a link is set to infinity if all wavelengths on the particular link are occupied by already provisioned lightpaths. After assigning link costs, in both routing algorithms, the *k* alternative routes for each connection request are computed by using the Dijkstra algorithm. If there is at least one common available wavelength on every link of the computed route, this route is stored in the set of candidate routes. Otherwise, if no route is found, the connection request is blocked. Next, the BER of candidate routes is calculated. In the case of shortest path routing, the shortest route of the set of candidate routes is selected first and the BER of this route is calculated. If the BER doesn't satisfy the signal quality requirement, i.e. single BER threshold independently from the class of connection requests, then the respective connection request is blocked. For traditional IABP algorithm and ICBR-Diff approach, the BER of all candidate routes is calculated. In the case of the traditional IABP algorithm, the route with minimum BER is selected and compared against the single BER threshold regardless of the signal quality requirement of the connection request. In contrast, in the case of ICBR-Diff approach, the BER of each candidate route is compared against the signal quality requirement of the connection request, i.e. against different BER thresholds depending on the class of the connection request. Among the various alternatives the feasible route (i.e. satisfying the signal quality requirement of the respective request) with maximum BER is selected (random picking is used for tie-breaking). In traditional IABP and ICBR-Diff, if none of candidate routes satisfies the signal quality threshold, the connection request is blocked. Finally, the first wavelength from a set of available wavelengths along the selected route is chosen (First-Fit) to form the lightpath for serving the connection request.

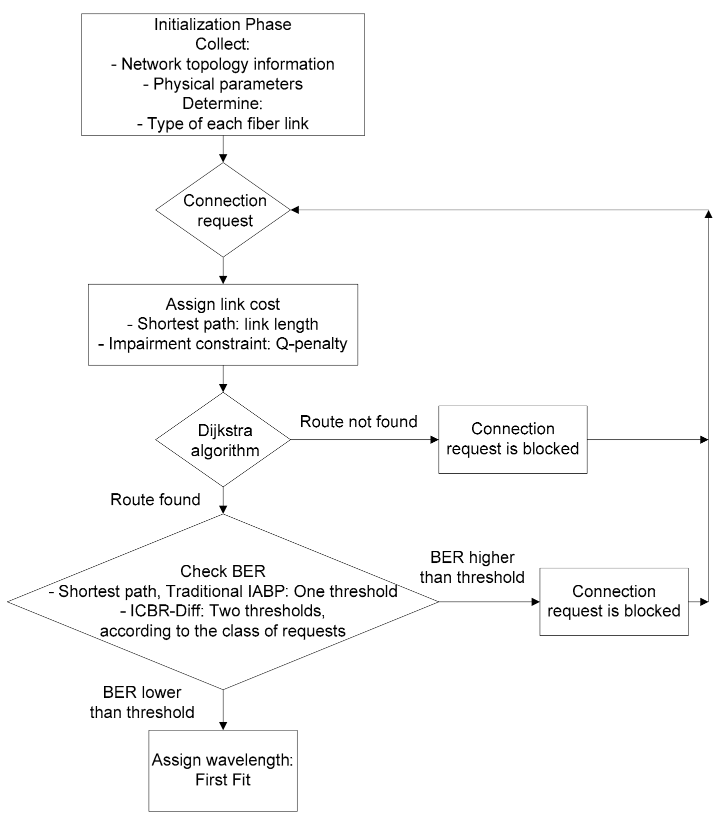


Figure 1. Flowchart of ICBR-Diff algorithm

3. PERFORMANCE EVALUATION

This section presents simulations results of the ICBR-Diff algorithm in a network exhibiting fiber heterogeneity. For the evaluation of our algorithm in the heterogeneous scenario we used the Pan-European test network topology (COST 239[10]) shown in Figure 2. The topology comprises 11 nodes and 26 bidirectional fiber links with 16 wavelengths per fiber.

For benchmarking purposes, we also evaluate two other provisioning algorithms already introduced in the previous section, namely shortest path and IABP. Essentially, these two approaches do not support service differentiation and thus connection requests are blocked if there is no route with BER less than a fixed threshold, i.e. BER=10^{-15}, irrespectively of the class that the connection request belongs to. Also ICBR with lightpath selection based on maximum BER, but without service differentiation, i.e. single BER threshold, is evaluated. Two configurations of traffic mixes of Class-1 and Class-2 (defined in Section 2) connection requests are considered: a) 30% of the overall traffic being of Class-1, while 70% of the traffic being of Class-2 and b) equal share of Class-1 and Class-2, i.e. each class amounting to 50% of the overall traffic.

The type of fiber in the network is randomly chosen adhering to the following five distinct schemes: a) 100% old fiber, b) 80% old fiber – 20% new fiber, c) 50% old fiber – 50% new fiber, d) 20% old fiber – 80% new fiber, and e) 100% new fiber. For each input network load value (measured in Erlangs), simulation experiments run until the 90%-confidence level of sampled blocking probability becomes less than 10% of the sampled mean.

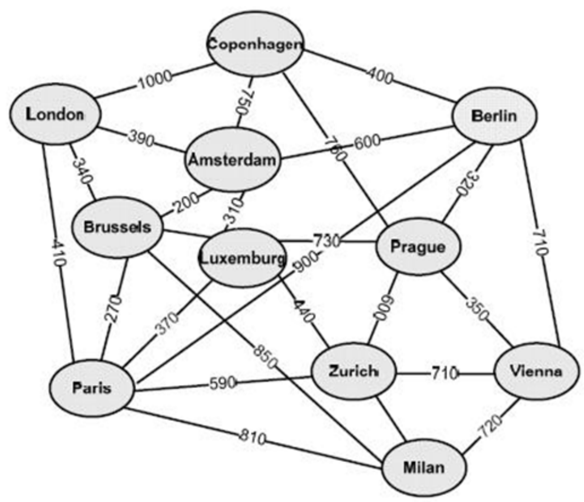
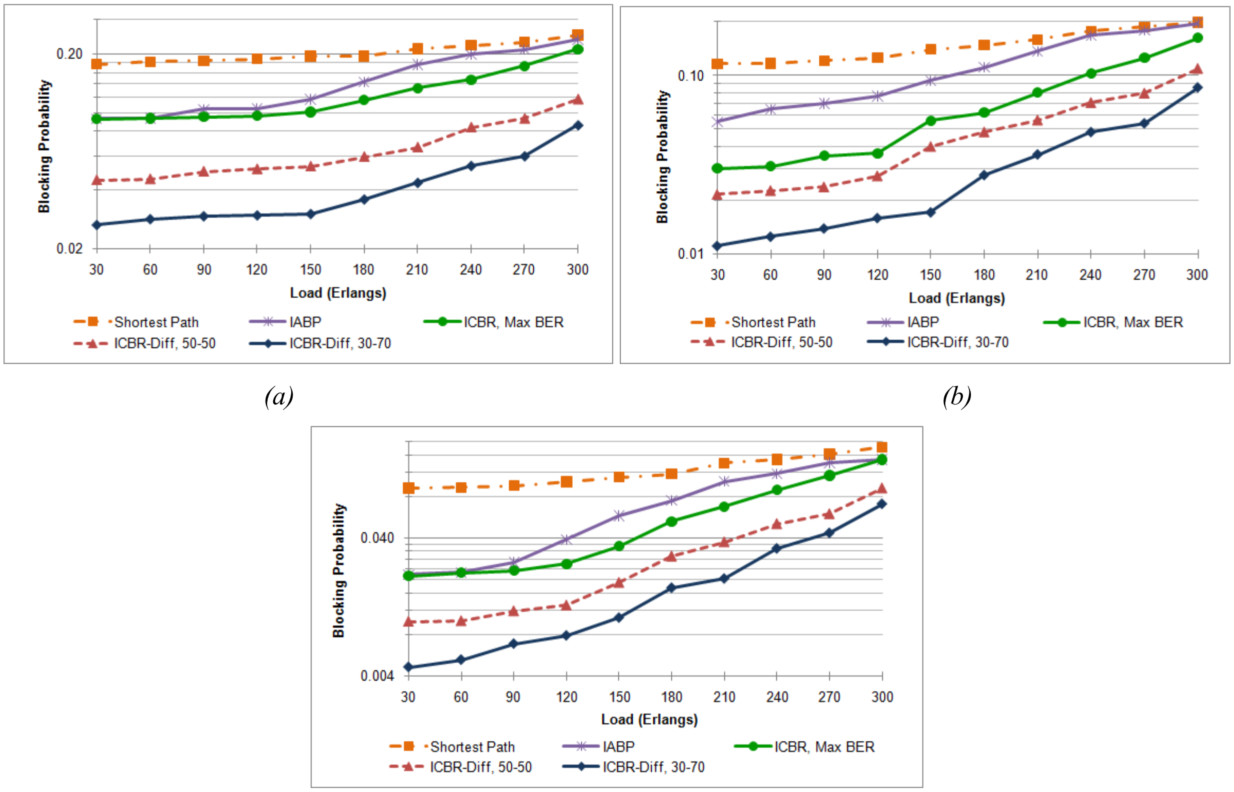


Figure 2. Pan-European test network (COST 239)

Our simulation results at 10 Gb/s bit rate are presented in Figure 3. The total blocking probability shown in Figure 3 accounts for both blocking due to insufficient resources, i.e. either no route or wavelength is available, and due to impairment constraints, i.e. when the candidate routes cannot meet the signal quality requirement. The results show a significant improvement in terms of blocking achieved by our ICBR-Diff algorithm across all cases of fiber heterogeneity, as compared to both shortest path and conventional IABP routing. Furthermore, the results reveal that ICBR with lightpath selection based on maximum BER exhibits slight improvement in blocking, as compared to the IABP algorithm. Specifically, in the 100%-old fiber scenario (Figure 3(a)), when Class-1 and Class-2 connection requests account for 30% and 70% of the total connection requests respectively, the benefit achieved by our algorithm is up to 17% and 15%, compared to shortest path and IABP algorithms, respectively.

Figure 4 shows blocking probability simulation results against fiber heterogeneity for a single, moderate loading of the network (150 Erlangs), i.e. without blocking due to insufficient resources. Evidently, a significant improvement in terms of blocking is achieved by ICBR-Diff across all fiber composition scenarios, compared to conventional routing algorithms.



(a) *(b)*

(c)

Figure 3. Blocking probability versus load (a) 100% old fiber, (b) 50% old fiber and (c) 100% new fiber

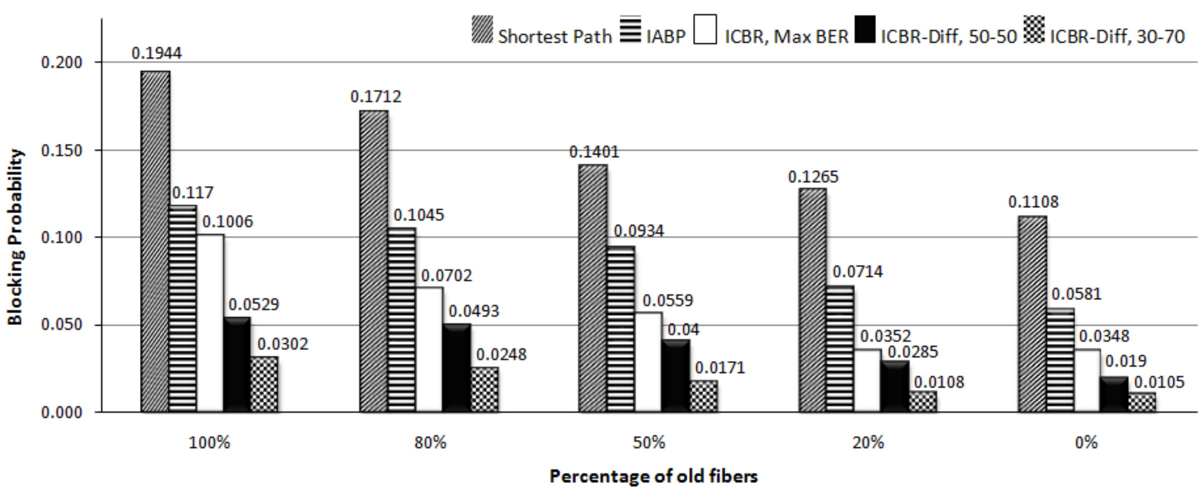


Figure 4. Blocking probability versus percentage of old fibers in the network

Another interesting finding is the high adaptability exhibited by ICBR-Diff throughout the various fiber composition scenarios. Most of the blocking improvement gained by ICBR-Diff is already taking place in the case with 100% old (more impaired) fibers. This is because by adapting the lightpath provisioning to the connection BER requirements and by choosing the lightpath with maximum BER that satisfies the connection requirements, the algorithm identifies a lightpath with acceptable BER performance with respect to the predefined threshold and avoids to unnecessarily take up a lightpath with a lower BER value compared to the threshold required. In this way, the best performing links remain available for future use, when new and more demanding connection requests, in terms of BER, are to be set up. This is not the case for shortest path and IABP, which either provision always the best performing available lightpath to each connection request (IABP), or they do not consider impairments at all in the path computation phase (shortest path). For this reason they tend to use up the less impaired resources first, thus needing newer and better performing fibers in the network to have performance comparable to ICBR-Diff.

4. CONCLUSIONS

This paper evaluated the performance of an ICBR algorithm with service differentiation (ICBR-Diff) in a network scenario with fibers of varying PMD characteristics. ICBR-Diff brings significant improvement in terms of blocking probability, when compared to conventional routing approaches. In this context, ICBR-Diff is able to offer high adaptability to heterogeneous fiber scenarios by assigning to connection requests resources that offer an acceptable level of performance, rather than unnecessarily high performance. Consequently, more efficient resource utilization is achieved.

ACKNOWLEDGEMENTS

This work was supported by the Network of Excellence “Building the Future Optical Network in Europe” (BONE), funded by the European Commission through the 7th ICT-Framework Programme and the EUREKA/CELTIC project “Management Platform for Next Generation Optical Networks” (MANGO).

REFERENCES

[1] I. Chlamtac, A. Ganz, and G. Karmi, "Lightpath communications: a novel approach to high bandwidth optical WANs," IEEE Transactions on Communications, vol. 40, no. 7, pp. 1171-1182, 1992.

[2] M. Farahmand, D. Awduche, S. Tibuleac, D. Atlas, “Characterization and representation of impairments for routing and path control in all-optical networks”, in Proc. Of Nat. Fiber Optic Engineers Conference (NFOEC), Dallas, TX, Sept. 2002.

[3] B. Ramamurthy, D. Datta, H. Feng, J.P. Heritage, B. Mukherjee, “Impact of transmission impairments on the teletraffic performance of wavelength-routed optical networks”, *Journal of Lightwave Technology*, vol.10, no. 17, pp. 1713-1723.

[4] R. Ramaswami, K.N. Sivarajan, “Optical networks a practical persective”, 2nd edition, Morgan Kaufmann, San Francisco, 2002.

[5] D. Breuer, H. J. Tessmann, A. Gladisch, H. M. Foisel, G. Neumann, H. Reiner, and H. Cremer, “Measurements of PMD in the installed fiber plant of Deutshe Telekom”, *2003 Digest of the LEOS Summer Topical Meetings,* pp. MB2.1/5-MB2.1/6, July 2003.

[6] G. Markidis, S. Sygletos, A. Tzanakaki and I. Tomkos, “Impairment Aware based Routing and Wavelength Assignment in Transparent Long Hual Networks”, *in Proc. Conf. on Optical Network Design and Modeling (ONDM)*, May 2007.

[7] Y. Huang, J. P. Heritage and B. Mukherjee, “Connection provisioning with transmission impairment consideration in optical WDM networks with high-speed channels”, *Journal of Lightwave Technology*, vol. 23, no. 3, pp. 982-993, Mar. 2005.

[8] A. Jirattigalachote, K. Katrinis, A. Tzanakaki, L. Wosinska and P. Monti, “Quantifying the benefit of BER-based Differentiated Path Provisioning in WDM Optical Networks”, *in Proc. of IEEE ICTON/RONEXT’09*, June 2009.

[9] C. D. Cantrell, “Transparent Optical Metropolitan-Area Networks”, *Invited presentation, LEOS 2003, The 16th Annual Meeting of the IEEE*, vol. 2, pp. 608-609, http://www.utdallas.edu/eecs/photec/Cantrell-LEOS-2003.pdf, Oct. 2003.

[10] P. Batchelor et al., “Study on the implementation of optical transparent transport networks in the European environment-Results of the research project COST 239”, *Photonic Network Communications*, vol. 2, no. 1, pp. 15-32, 2000.
[11] Traffic Measurements and Models in Multi-Service Networks project, Celtic project, “TRAMMS IP Traffic report no. 1, April 2008”, *http://projects.celtic-initiative.org/tramms/*.
[12] Traffic Measurements and Models in Multi-Service Networks project, Celtic project, “TRAMMS IP Traffic report no. 3, June 2008”, *http://projects.celtic-initiative.org/tramms/*.