An Hybrid Prediction-based Routing Approach for Reducing Routing Inaccuracy in Optical Transport Networks

Wilson Ramirez*, Xavier Masip-Bruin*, Eva Marín-Tordera*, Marcelo Yannuzzi†, Anny Martinez*†,
Sergio Sánchez-López*, Victor López‡
*Advanced Network Architectures Lab (CRAAX), Technical University of Catalonia (UPC), Spain
†Networking and Information Technology Lab (NetIT Lab)
Emails: {wramirez, xmasip, eva, yannuzzi, annym, sergio}@ac.upc.edu
‡Telefonica I+D, Spain, vlopez@tid.es

***Abstract*—The advent of network technologies such as Automatically Switched Optical Networks (ASON) and Generalized Multiprotocol Label Switching (GMPLS) pave the way to the deployment of flexible optical transport networks (OTNs). The flexibility of OTNs is a feature highly demanded in dynamic scenarios where lightpaths are continuously set up and torn down on a short-term basis. Unfortunately, the availability and accuracy of network state information in dynamic scenarios are both limited, causing a severe impact on both performance and scalability of Routing and Wavelength Assignment (RWA) algorithms. In this paper we devise a promising routing scheme so-called Hybrid Prediction-based Routing (HPBR). HPBR combines prediction strategies with a novel method to select the most suitable routing metric, aiming at reducing both the dissemination of network state information and the blocking probability. Our findings validate that the proposed scheme significantly reduces the blocking probability compared with other routing schemes, while avoiding the need to periodically disseminate network state information.**

***Index Terms*—Prediction Routing; Routing Inaccuracy**

I. INTRODUCTION

Optical Transport Networks (OTNs) provide the flexibility and transmission capacity for suitable handling the skyrocketing demand of bandwidth required by future Internet applications. One of the building blocks of OTNs is the Wavelength Division Multiplexing (WDM) technology. WDM allows a single optical fiber patch to simultaneously convey different wavelengths. To properly select a lightpath (both wavelength and path) Routing and Wavelength Assignment (RWA) algorithms jointly with control plane protocols such as Automatically Switched Optical Networks (ASON) and Generalized Multiprotocol Label Switching (GMPLS) are commonly used.

The performance of an RWA algorithm is severely affected in dynamic scenarios where lightpaths are continuously setup and tear down on a short-term basis. This effect is mainly motivated by two issues: 1) the connection setup delay; and 2) the inaccuracy of the network state information [1]. In light of this, the study of RWA in the context of dynamic scenarios is gaining momentum in network research, motivated by the fact that nowadays internet applications such as Video on demand (VoD) or bulk transfer data, demand huge bandwidth and connectivity in an agile manner, which undoubtedly can overload the network with a high volume of Connection Requests (CRs).

On a source-based routing scenario–one of the ASON recommendations [2]–, the availability and accuracy of network state information have a profound impact on both performance and scalability of RWA algorithms. Indeed, inaccurate network state information might result in sub-optimal path selections that potentially lead to an increase of the blocking probability. The main factors of inaccurate network state information are infrequent state information dissemination and high propagation delays.

Two main vehicles to offset the negative effects caused by inaccurate network state information are: i) the use of multi-fiber systems; and, ii) increase the frequency of network state information dissemination, hereinafter referred to as the update period. Unfortunately, low update periods cause overhead concerns that leads to scalability issues, specifically on dynamic and large network scenarios. Even with unrealistic updating periods (consider that the minimum update period defined by OSPF is 5 seconds), i.e., flooding update messages per network state change, network state information might still be inaccurate [3]. On the other hand, the use of multi-fiber systems represents a high Capex cost.

The rationale of this paper is to deal with the *"routing inaccuracy problem"* in OTN network, specifically in a Wavelength-Interchangeable network. That is, we do not consider the wavelength continuity constraint which defines that a lightpath can be solely established if the same wavelength is available along the path selected from the source to the destination Wavelength Router (WR).

In order to deal with the routing inaccuracy problem we propose a routing novel scheme so-called Hybrid Prediction-based Routing (HPBR). HPBR exploits both prediction techniques and a novel method to

978-1-4799-3872-8/14/$31.00 ©2014 IEEE

select the most suitable routing metric according to the offered load conditions. The main advantage of HPBR is that its performance (blocking probability) is not affected by the update period since the network state information required by HPBR is locally computed by each source WR. We shall show that HPBR yields a low blocking probability in comparison with other routing schemes without requiring network state information dissemination.

The rest of this paper is organized as follows. Section II delves into the state of the art on the routing inaccuracy problem. Section III introduces the proposed routing scheme. Section IV describes the simulation model and the network scenarios used. Section V presents the obtained simulation results. Finally, Section VI provides final conclusions and future line of work.

II. RELATED WORK

The study of RWA algorithms has been widely studied over the years [4]. Nonetheless, a small percentage of these studies take into account inaccurate network state information. In this section, we introduce in a nutshell several contributions specifically related to the routing inaccuracy problem.

The study presented in [5] is a pioneer work dealing with the routing inaccuracy problem in the IP domain, where authors focus on delay and bandwidth constraints applications, and propose probabilistic models to express the uncertainty of network state information. More recent works such as [6] propose a so-called Bypass-Based Routing, where authors claim to overcome the performance of the Safety-based Routing. The Bypass-Based Routing is based on a novel metric to model uncertainty combined with a mechanism that bypasses congested links –whenever a path selection is sub-optimal.

On the other hand, there are several studies available in the literature related to the routing inaccuracy problem in optical networks. The study in [7] extends the BBR algorithm for optical networks considering wavelength conversion. Whereas authors in [8] provide an analytical model to assess the performance of source-based routing in optical networks with inaccurate network state information. The study in [9] also addresses the routing inaccuracy problem in optical networks, where authors propose a parallel reservation scheme. Nevertheless, a handicap of this approach is its high consumption of network resources.

The aforementioned studies require some network state dissemination whatsoever –even thought this one is significantly reduced. It was the study presented in [3] which plunges into the routing inaccuracy problem on OTNs, by guarantying that the dissemination of network state information is restricted solely to topological changes. To this end, authors propose the Predictive-Based Routing algorithm (PBR) based on prediction branch techniques introduced in [10]. Basically, PBR relies on a two-bit counter to predict a route availability. On this basis, if a route is selected, but a certain connection cannot be provisioned along this route, its predictive counter value is increased. Conversely, if the connection can be provisioned along a route, its predictive counter is decreased.

Motivated by the tradeoff between blocking probability and network state information achieved by PBR, the studies available in [11] and [12] also use the prediction strategies for OTN. On one hand, authors in [11] combine both BBR and PBR scheme– obtaining the so-called Balanced Vulnerable Predictive Path (BVP2)–scheme, aiming at improving the performance of PBR. On the other hand, authors in [12] propose a RWA scheme referred to as Fuzzy-based Routing (FRA), that not only combines both BBR and PBR, but it is also enriched with fuzzy based techniques to enhance the modeling of route availability.

In this paper, we propose a source-based routing scheme for addressing the routing inaccuracy problem in OTNs referred to as Hybrid Prediction-based Routing (HPBR). HPBR also exploits the use of prediction techniques but differs from the schemes proposed in [3], [11], [12] in several aspects.

First, the schemes proposed in [3, 11-12] assume a two-bit predictive counter assigned locally by each WR for each route –predictive counter per route. We adopt a fine-granularity approach. To this end, each WR keeps track of optical links availability by means of a two-bit counter –predictive counter per link. Secondly, HPBR is not bounded to a unique routing metric; it dynamically selects the most suitable metric according to the offered load conditions. We shall show that a fine-granularity approach is most suitable for predicting routes availability in comparison with coarse-granularity predictive counters.

III. THE HPBR ALGORITHM

In this section we present the HPBR mechanism. Moreover, the symbols used in this paper are listed in Table I.

HPBR exploits the use of two-bit counters to predict routes availability. A counter value is increased or decreased as follows: $p_i^{(s)} = p_i^{(s)} + 1 \ iff$ a connection along link i is blocked and $p_i^{(s)} < 3$; and $p_i^{(s)} = p_i^{(s)} - 1 \ iff$ a connection along link i can be successfully provisioned and $p_i^{(s)} > 0$. The rationale behind adopting two-bit predictive counters is because this is enough to keep historical behavior of routes. Otherwise, a low counter value is unable to properly model a route availability, whereas higher values add an enormous degree of hysteresis which causes sub-optimal paths selections –driven by the inertia generated by a high counter value.

Whenever a route must be selected to provision a connection demand, the availability of a route is locally computed by each WR according to the offered load conditions. For moderate offered loads (Moderate-Dynamic scenarios, see Section IV) the availability of a route is computed as shown in Equation (1), where a high value of $\mathcal{L}_j^{1(s)}$ means that route j may be unavailable, the contrary occurs with low values.

Table I

LIST OF SYMBOLS.

Symbols	Meaning
$G(V, E)$	Directed graph such as V is the set of WRs and E is the set of optical links.
$p_i^{(s)}$	Predictive counter of link i locally computed by a WR s, where $s \in V$, $i \in E$, and $p_i^{(s)} \in \{0, 1, 2, 3\}$.
$\mathcal{L}_j^{1(s)}$	Availability of route j locally computed by a WR s for a Moderate-Dynamic scenario.
$\mathcal{L}_j^{2(s)}$	Availability of route j locally computed by a WR s for a Highly-Dynamic scenario.
$v_i^{(s)}$	Vulnerability degree of link i locally computed by a WR s.
$b_i^{(s)}$	The residual bandwidth of link i locally computed by a WR s.
ϵ	Predefined threshold defining the degree of inaccuracy tolerated by HPBR.
λ	A wavelength unit.
b_{req}	Optical bandwidth demanded by a connection request.
$C_j^{1(s)}$	The cost of route j locally computed by a WR s for a Moderate-Dynamic scenario.
$C_j^{2(s)}$	The cost of route j locally computed by a WR s for a Highly-Dynamic scenario
N_j	Number of hops along route j.
$V_j^{(s)}$	Vulnerability of route j locally computed by WR s.

$$\mathcal{L}_j^{1(s)} = \sum_{i \in j} v_i^{(s)} p_i^{(s)} \tag{1}$$

It is worth mentioning that the vulnerability degree ($v_i^{(s)}$) is a concept introduced by [11] and used to model whether an optical link may lead to a connection blocking. The vulnerability degree of a link is computed as shown in Equation (2).

$$v_i^{(s)} = \begin{cases} 1, & iff\ 1 - \frac{b_{req}}{b_i^{(s)}} < \epsilon \\ 0, & otherwise \end{cases} \tag{2}$$

The vulnerability degree of a link is selected according to the parameter ϵ, so-called blocking factor, which is a predefined threshold reflecting the degree of inaccuracy tolerated by HPBR. Thus, parameter ϵ must be properly set according to the offered load conditions. Indeed, the blocking factor modeling is left for future work.

In addition, notice that a predictive counter value is only considered for computing the route availability whenever the link is considered vulnerable. Therefore, even though the value of a predictive counter of a link is greater than zero, if this link is not vulnerable its predictive counter does not affect the availability of a route.

On the other hand, for a high offered loads (a Highly-Dynamic scenario, see Section IV) the availability of a route is computed in a similar manner as $\mathcal{L}_j^{1(s)}$, but the vulnerability degree is not taken into account for its computation, cf. Equation (3).

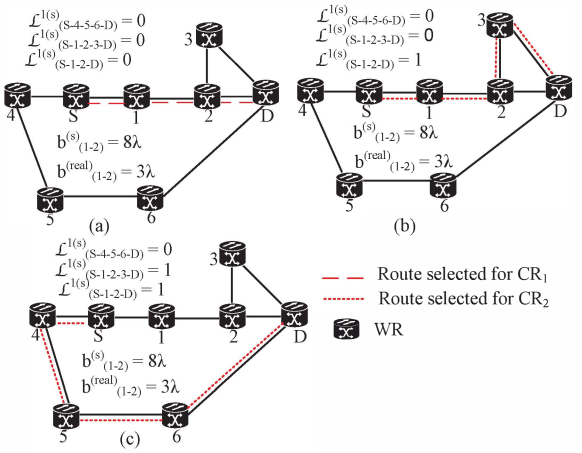

Figure 1. a) and b) Coarse-granularity predictive counters; c) Fine-granularity predictive counters.

$$\mathcal{L}_j^{2(s)} = \sum_{i \in j} p_i^{(s)} \tag{3}$$

In addition, we decrease the hysteresis degree of a link counter, such as $p_i^{(s)} = p_i^{(s)} + 2\ iff$ a connection along link i is blocked and $p_i^{(s)} < 2$; and $p_i^{(s)} = p_i^{(s)} - 2\ iff$ a connection along link i can be successfully provisioned and $p_i^{(s)} > 0$.

For the purpose of explaining the reasons that motivated us to adopt a fine-granularity for the predictive counters, we consider the topology depicted in Fig. 1a, where source-based routing is assumed. A connection request (CR_1) needs to be provisioned demanding the allocation of 4λ with WRs S and D as source and destination respectively. As a consequence, route $S-1-2-D$ is selected, but it cannot be provisioned due to lack of bandwidth. This occurs because of the inaccuracy of the network state information in WR S, which reflects $b_{1-2}^{(s)}$ with a residual capacity of 8λ. However, the real residual bandwidth of link $1-2$ is 3λ, less than the bandwidth requested by CR_1, i.e., the state information stored in WR S is inaccurate. If predictive counters per route (coarse-granularity counters) are used, then the predictive counter of route $S-1-2-D$ is increased.

Consider now the scenario depicted in Fig. 1b, where a second connection request (CR_2) reaches WR S with similar characteristics (5λ of requested bandwidth and WRs S and D as endpoints) as CR_1. As a result, WR S avoids selecting route $S-1-2-D$ (due to its predictive counter value) and attempts to provision a connection along route $S-1-2-3-D$; however, CR_2 cannot be provisioned. This occurs because link $1-2$ does not have enough bandwidth to allocate CR_2, but a coarse-granularity counter does not capture the unavailability of link $1-2$; hence route $S-1-2-D$ is shown as available.

After carefully observing the scenarios depicted in Fig. 1a and Fig. 1b, an intuitive thought is to use fine-granularity predictive counters. In light of this, take into account the scenario depicted in Fig. 1c. When

CR_2 reaches WR S this one captures the unavailability of route $S-1-2-3-D$. This is because the counter of link $1-2$ (a link part of route $S-1-2-3-D$) is not 0; hence, route $S-4-5-6-D$ is selected –all of the links forming this route have their predictive counter values on 0. By means of fine-granularity predictive counters the blocking probability is reduced, as we demonstrate and validate by the simulation results presented in Section V.

As such, HPBR uses fine-granularity predictive counters, but it also uses two metrics for routing purposes. On one hand, the first metric, computed as shown in Equation (4), is an enhancement of the metric presented by [11] (a previous work by the authors). This metric can be categorized as a dynamic metric since has certain dependency on variable network state information (hence, potentially inaccurate) such as link bandwidth and link vulnerability and is used for Moderate-Dynamic scenarios. Notice that $V_j^{(s)}$ is the vulnerability of route j, where $V_j^{(s)} = \sum_{i \in j} v_i$. Finally, b_{min} is the minimum bandwidth available on the links forming route j, such as $b_{min} = min\left(b_i^{(s)}\right) \; \forall i \in j$.

$$C_j^{1(s)} = \frac{\mathcal{L}_j^{1(s)}}{N_j - 1} + N_j \left(\frac{1}{b_{min}}\right)\left(V_j^{(s)} + 1\right) \qquad (4)$$

Since the availability of a route (left term of Equation (4)) usually has more weight than other parameters of Equation (4), we divide it by the route length in order to balance the weight of each parameter. In addition, if a route vulnerability is 0, HPBR does not rely only on the predictive counter value to compute C_j^1, see the right term of Equation (4). This issue was not addressed by authors in [11].

On the other hand, the other metric used by HPBR, cf. Equation (5), can be categorized as a quasi-permanently metric since it has a low dependency of variable network state information, i.e., it avoids both vulnerability and bandwidth parameters this metric is used for Highly-Dynamic scenarios. In Section IV, we delve into the issues driving the use of an hybrid metric approach.

$$C_j^{2(s)} = \frac{\mathcal{L}_j^{2(s)}}{N_j - 1} + N_j \qquad (5)$$

IV. MODEL METHODOLOGY

In order to ensure realistic findings, we build up a simulation model of an OTN scenario based on the NSFNet topology (see Fig. 2) using the well-known network simulator OMNeT++ [13]. All the plotted values have a 95% confidence interval not larger than 0.5% of the plotted values. We also adopt two type of dynamic scenarios:

1) **Moderate-Dynamic or Quasi-Incremental scenario**. In this scenario the connection requests arrivals (CRA) for each WR are as follows: $CRA_1(t_1), CRA_2(t_1+t), \ldots CRA_n(t_{n-1}+t)$, such as t and t_n are Poisson-distributed.

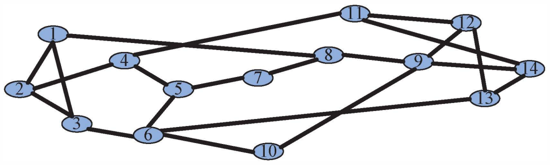

Figure 2. The 14-nodes, 21 links NSFNet topology.

2) **Highly-Dynamic scenario.** In this scenario the CRAs for each WR are as follows: $CRA_1(t_1), CRA_2(t_2), \ldots CRA_n(t_n)$, such as t_n is Poisson-distributed..

In the performed trials the following settings were assumed:

- Holding time per connection is exponential distributed with a mean never exceeding ten times the CRA time.
- The average bandwidth requested per connection is poisson distributed with a mean never exceeding the 10% capacity of an optical link respectively.
- WRs with 80 channels on a 50 GHz fixed-grid, which is one of the channel spacing standards defined by the International Telecommunication Union (ITU).
- In order to reduce path computation complexity a Fixed-Alternate routing approach was assumed, i.e., 4 precomputed (candidate) shortest-paths per source WR, obtained offline by means of Dijkstra's algorithm.
- The time required by a connection setup is neglected.
- Reattempt is not done once a connection is blocked.
- All WRs support full wavelength conversion.
- We assume a single fiber system.
- Once a connection is established it cannot be reconfigured during its lifetime.

Based on extensive simulations, the obtained results (presented in Section V) lead us to consider that for Moderate-Dynamic scenarios a dynamic metric as the one shown in Equation (4) provides good performance in comparison with other routing schemes. However, for Highly-Dynamic scenarios a quasi-permanently metric based on hops, such as the one shown in Equation (5) exhibits a better performance. This is because as the inaccuracy increase –since the available bandwidth is rapidly changing— it is better to rely on routes that span less hops in order to use less bandwidth, and add less inaccuracy. Indeed, our numerical results validate that in Highly-Dynamic scenarios selecting paths that span several hops routes in order to avoid a potential connection blocking is not optimal. Having said so, relying on more network state information may be counterproductive. The performance of static (permanently metric) and dynamic routing has been discussed by [14]. Nevertheless, authors do not consider inaccurate and local network state information.

Algorithm 1 Overview of the metric adaptation mechanism of HPBR.

```
Input: ($dest$, $b_{req}$, $timestamp$)
Output: ($metric$)
  {$dest, b_{req}$ and $timestamp$ are the destination, bandwidth, and arrival time of the requested lightpath respectively.}
  if $H.size() < th_1$ then
    $H.append(dest)${$H$ is a set containing different lightpath's destinations, the maximum size of $H$ ($H.size()$) is determined by $th_1$, $append()$ is a method that inserts the specified content into a given set. }
    $RT.append\,(timestamp)$
  else
    $Destinations = distinct(H)${$distinct$ is a method returning a set of distinct elements of a set ($H$). }
    for $i$ in range $(0, size\,(RT) - 1)$ do
      $Delta.append\left[abs\left(RT_{[i+1]} - RT_{[i]}\right)\right]${rate of change of the connection requests.}
    $Delta\_value$=$Distinct2(Delta)${$Distinct2$ is a method returning the amount of elements with values less than $th_3$, such that $th_3$ is a predefined threshold.}
    if $|Destinations| > th_2$ and $Delta\_value > 0.7 \times th_1$ then
      $metric = Equation\,(5)$
      $Set\ Increment/Decrement\ Values\ of\ counters$
    else
      $metric = Equation\,(4)$
      $Set\ Increment/Decrement\ Values\ of\ counters$
    $RT$, $H = \emptyset${Reinitialize $H$ and $RT$}
```

HPBR collects information such as destination and arrival time of CRs in order to evaluate the network conditions. Based on this evaluation HPBR selects either Equation (4) or (5) to compute route costs. The overall procedure of how this is done is elucidated in Algorithm 1. As it can be observed, if a WR receives a high amount of CRs during a short period of time (determined by variable $Delta\_value$ in Algorithm 1) and the destination WRs (variable $Destinations$ in Algorithm 1) of these requests are highly heterogeneous, then HPBR computes $C_j^{(s)}$ based on Equation (5), otherwise it uses Equation (4). In Algorithm 1, th_1 determines the amount of collected information; whereas th_2 specifies when the condition of CRs with highly-heterogeneous destinations is met; finally, th_3 specifies temporal proximity of the CRs. The threshold values of th_1, th_2 were set to 20, 8 respectively, whereas th_2 value was set to 4 units of time.

V. SIMULATION RESULTS

In this section, we present the simulation results related to the proposed scheme namely HPBR and other similar works available in the literature such as PBR, FRA, BVP2 (we adapted BVP2 for OTNs), the well-known Least-Congested Path (LCP), which among the evaluated schemes is the only one that requires periodically dissemination of network state information, and HOPS, which uses a routing metric based exclusively on the number of hops along a path.

On one hand, Fig. 3 shows the blocking probability for a Moderate-Dynamic scenario. In this scenario LCP and HPBR have a better performance. However, the performance of HPBR is not affected by the update time interval, as it is the case with LCP. This is because in HPBR the dissemination of network state information is solely restricted to topological changes. Notice that the performance of a prediction routing scheme based on coarse-granularity predictive counters such as PBR is not optimal because of the high offered loads. Other similar schemes such as BVP2 and FRA yield a better performance, even though their performance is not as good as a fine-granularity approach such as HPBR.

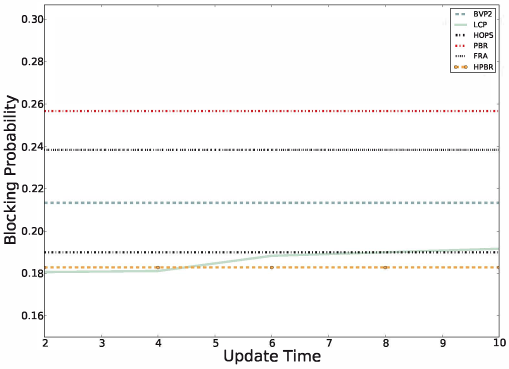

Figure 3. Blocking probability for a Moderate-Dynamic scenario with 100 requests per WR, 6 WRs as sources, average holding time and CRA time of 4 units; average b_{req}=10% of total link capacity; and ϵ=5%.

On the other hand, Fig. 4 shows the blocking probability for a Highly-Dynamic scenario. The purpose of this trial is to simulate a network heavily loaded of CRs. For this purpose we select a holding time ten times higher than the CRA time, i.e., increase the number of active connections in the network at any time.

In Highly-Dynamic scenarios the performance of a routing scheme dependent on the accuracy of network state information such as LCP is significantly degraded. This is not the case for prediction based routing schemes.

Finally, Fig. 5 presents the simulation results related to a mixture a Moderate-Dynamic and a Highly-Dynamic scenario, where we opt to gradually increase the total of possible destinations –increase the number of active connections at any moment– for a CR. In this scenario, HPBR switches from computing routes as shown Equation (4) to compute routes using Equation (5), once it detects (according to Algorithm 1) that the network conditions entail a different network scenario– based on the offered load.

It is important to notice how the performance of a static routing strategy such as HOPS improves as the inaccuracy degree increases, i.e., more active connections at any moment. This behavior was validated by a similar approach followed by authors in [14]. This motivated us to incorporate an hybrid metric system for HPBR.

Notice that for a low total of distinct destinations

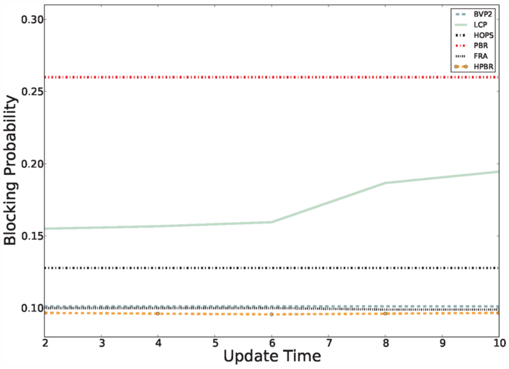

Figure 4. Blocking probability for a Highly-Dynamic scenario with 100 requests per WR, 6 WRs as sources, average holding time and CRA time of 100 units and 10 units respectively; average b_{req}=2% of total link capacity; and ϵ=5%.

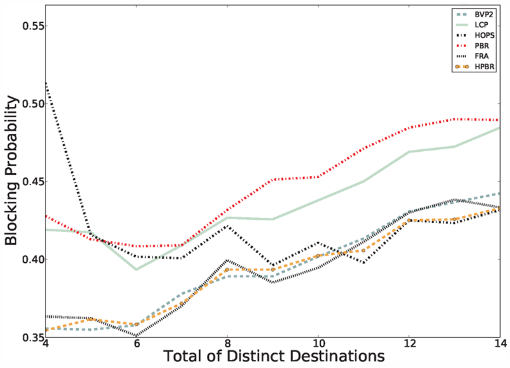

Figure 5. Blocking probability for a mixture of a Moderate and a Highly-Dynamic scenario with 200 requests per WR, 3 WRs as sources, average holding time and CRA time of 4 units respectively; average b_{req}=5% of total link capacity; and ϵ=5%.

FRA shows a low blocking probability but for high total of distinct destinations its performance is reduced. The opposite occurs with HOPS scheme. However, HPBR shows low blocking probability independently of the network scenario type. A lesson learned from the obtained simulation results is that fine-granularity predictive counters are the best option for addressing the routing inaccuracy problem in OTN networks.

VI. CONCLUSIONS

The contribution of this paper focuses on a novel routing scheme based on prediction techniques referred to as Hybrid Prediction-based Routing (HPBR). HPBR uses two routing metrics according to the offered load conditions both leveraging prediction techniques in order to deal with the routing inaccuracy problem in Optical Transport Networks (OTNs). The main difference of HPBR compared with similar prediction routing schemes available in the literature (also dealing with the routing inaccuracy problem) is that it adopts fine-granularity predictive counters for the purpose of predicting a route availability. Obtained results validate that the proposed scheme shows a better performance related to the blocking probability in distinct dynamic scenarios.

As a future line of work, we intend to study how both the network topology and different blocking factors may impact on the metric type used for routing purposes and the performance of HPBR respectively. In addition, we intend to extend prediction techniques to deal the routing inaccuracy problem considering the wavelength continuity constraint.

ACKNOWLEDGMENTS

This work was supported by the Spanish Ministry of Economy under contract TEC2012-34682, and the Catalan Research Council (CIRIT) under contract 2014 SGR 371.

REFERENCES

[1] *H. Zang, J. Jue, L. Sahasrabuddhe, R. Ramamurthy, and B. Mukherjee, "Dynamic lightpath establishment in wavelength routed WDM networks,"* Communications Magazine, IEEE, *vol. 39, no. 9, pp. 100–108, 2001.*

[2] ITU-T Rec. 68080/4.1304, Architecture for the Automatically Switched Optical Network (ASON)., *Std., November 2001.*

[3] *E. Marin-Tordera, X. Masip-Bruin, S. Sanchez-Lopez, J. Sole-Pareta, and J. Domingo, "The prediction-based routing in optical transport networks."* Computer Networks, *vol. 29, pp. 865–878, 2006.*

[4] *H. Zang and J. P. Jue, "A review of routing and wavelength assignment approaches for wavelength-routed optical WDM networks,"* Optical Networks Magazine, *vol. 1, pp. 47–60, 2000.*

[5] *R. A. Guérin, R. A. G. Erin, and A. Orda, "QoS Routing in Networks with Inaccurate Information: Theory and Algorithms,"* IEEE/ACM Transactions on Networking, *1997.*

[6] *X. Masip-Bruin, S. Sanchez-Lopez, J. Sole-Pareta, and J. Domingo-Pascual, "QoS routing algorithms under inaccurate routing for bandwidth constrained applications," in* Communications, 2003. ICC '03. IEEE International Conference on, *vol. 3, 2003, pp. 1743–1748 vol.3.*

[7] *Y. Luo, Y. Zhang, and W. Gu, "A new method for solving routing and wavelength assignment problems under inaccurate routing information in optical networks with Conversion Capability," in* Communications and Photonics Conference and Exhibition (ACP), 2009 Asia, *2009, pp. 1–2.*

[8] *S. Shen, G. Xiao, and T. H. Cheng, "The Performance of Periodic Link-State Update in Wavelength-Routed Networks," in* Broadband Communications, Networks and Systems, 2006. BROADNETS 2006. 3rd International Conference on, *2006, pp. 1–10.*

[9] *J. Liu, G. Xiao, K. Lu, and I. Chlamtac, "An Evaluation of Distributed Parallel Reservations in Wavelength-Routed Networks,"* Selected Areas in Communications, IEEE Journal on, *vol. 25, no. 9, pp. 27–39, 2007.*

[10] *J. E. Smith, "A Study of Branch Prediction Strategies," in* Proceedings of the 8th Annual Symposium on Computer Architecture, *ser. ISCA '81. Los Alamitos, CA, USA: IEEE Computer Society Press, 1981, pp. 135–148. [Online]. Available: http://dl.acm.org/citation.cfm?id=800052.801871*

[11] *X. Masip-Bruin, E. Marin-Tordera, M. Yannuzzi, R. Serral-Gracia, and S. Sanchez-Lopez, "Reducing the effects of routing inaccuracy by means of prediction and an innovative link-state cost,"* Communications Letters, IEEE, *vol. 14, no. 5, pp. 492–494, 2010.*

[12] *E. Ahvar, E. Marin-Tordera, M. Yannuzzi, X. Masip-Bruin, and S. Ahvar, "FRA: A new fuzzy-based routing approach for optical transport networks," in* Networks and Optical Communications (NOC), 2012 17th European Conference on, *2012, pp. 1–6.*

[13] *http://www.omnetpp.org/, [Online; accessed February-2014].*

[14] *A. Zapata-Beghelli and P. Bayvel, "Dynamic Versus Static Wavelength-Routed Optical Networks,"* Lightwave Technology, Journal of, *vol. 26, no. 20, pp. 3403–3415, 2008.*