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Prediction-based routing as RWA in multilayer traffic engineering

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Abstract Multilayer traffic engineering (MLTE) allows coping with ever-increasing and varying traffic demands in IP-over-Optical multilayer networks. It utilizes cross-layer TE (Traffic Engineering) techniques to provision optical lightpath capacity to the IP/MPLS (Internet Protocol/ Multi-Protocol Label Switching) logical topology on-demand. Such provisioning however causes optical connection arrival rates that pose strong performance requirements to Routing and Wavelength Assignment (RWA) strategies. Collecting up-to-date network information for the RWA with rapidly changing network states can be quite difficult. Exposing optical layer state information to the IP layer in the overlay model, or transforming this optical layer information in a workable representation in an integrated control plane is similarly problematic. Prediction-Based Routing (PBR) has been proposed as a RWA mechanism for optical transport networks; it bases routing not on possibly inaccurate or outdated network state, but instead on previous connections set-up. In this article, we propose to implement PBR as the RWA mechanism in the optical layer of a multilayer network, and use the predictive capabilities of PBR to expose dynamic optical network information into the multilayer traffic engineering algorithm with minimal control plane overhead. Some simulations show the benefits of using the PBR in the optical layer for MLTE purposes.

Keywords Multilayer traffic engineering · RWA · Prediction-based routing · OTN · ASON

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1 Introduction

Continuously growing Internet traffic demands are forcing network operators to introduce high capacity and reliable transport networks, such as the optical transport networks (OTN). On the other hand, new Internet applications pose greater bandwidth demands and require greater network flexibility and traffic delivery guarantees.

An OTN consists of switching nodes (Optical Cross-Connect, OXC) interconnected by wavelength-division multiplexed (WDM) fiber-optic links that provide end-to-end lightpaths between a source-destination node pair, spanning multiple fiber links. When an OTN includes automatic switching capabilities, it is referred to as an automatically switched optical network (ASON).

Internet applications are carried on IP-based packet switched networks. The introduction of MPLS functionality has allowed decoupling the routing and forwarding of packets. This provides improved traffic engineering possibilities, which cater to the shifting of traditionally non-IP services such as telephony, video, etc. onto a single IP/MPLS converged network layer. Given the high traffic demands, an optical transport network layer provides these IP/MPLS networks with the required capacity (lightpaths). Multilayer traffic engineering (MLTE) extends the classic IP/MPLS layer TE into the optical layer, utilizing cross-layer TE concepts based on optical layer switching flexibility, in addition to IP/MPLS routing and logical topology creation techniques.

A full multilayer IP-over-Optical routing and TE strategy also requires some sort of optical routing policy. Source-based routing is one of the recommendations stated in the ASON specifications [1]. In source-based routing, routes are dynamically (or adaptively) computed in the source nodes, based on the routing information contained in their network state databases, reacting to incoming traffic demands. Unlike traditional IP networks, where the routing process only involves physical path selection, optical networks typically have a wavelength continuity constraint and require wavelength selection as well; there the problem is stated as routing and wavelength assignment (RWA).

RWA and traffic engineering attempt to optimize network performance metrics such as capacity usage, total throughput, cost or general network parameters which directly correspond to QoS parameters such as delay, packet loss, etc. In any case, such online optimization requires operation of TE and RWA algorithms based on available network information. For IP/MPLS-based TE techniques, this can be data extracted from IP/MPLS nodes (e.g., IP/MPLS link saturation), both passive and active end-to-end QoS measurements or other kinds of information that may be provided from the control and management plane. RWA relies on per-fiber utilized capacity statistics, which for the typical case of wavelength selective optical networks, should be detailed on the wavelength level. In general, one can say that both IP/MPLS and optical routing algorithms allow for better optimization when available network information is more detailed.

However, the extraction of detailed measurements often takes time both because of the monitoring process and the subsequent flooding of the information over the network. This may cause delays in algorithm response time and general network performance degradations. The already difficult task of extracting and presenting full information toward online routing algorithms becomes even more problematic when one wants to use such detailed optical information for cross-layer optimization. The prevalence of overlay based IP-over-Optical networks poses an additional hurdle; even if detailed optical layer information is somehow available, technical and confidentiality limitations will prevent full access to this monitoring data for the IP/MPLS MLTE strategy.

The work in this article is based on IP/MPLS and RWA algorithms which take this limited availability of information into account. The IP/MPLS multilayer traffic engineering requires only IP/MPLS link load, not full information about the forwarding path of every IP/MPLS LSP. The RWA algorithm based on the PBR mechanism uses predictive source routing which does not need information about wavelength channel utilization in optical fibers at all, apart from allocation on the fibers incident to the routing source node. In this work, we will show how these two algorithms can be integrated, in order to allow optical layer load information to be used in optimizing network performance under the overlay network model constraints.

Section 2 briefly presents the proactive multilayer traffic engineering and prediction-based routing RWA, as well as other related work found in literature from the respective research domains. Section 3 details the method used for integrating the MLTE and PBR strategy, while Sect. 4 validates this effort with some simulation results. Finally, Sect. 5 presents the conclusions of this article.

2 Overview of previous work

This section provides both an overview of related work in both the IP/MPLS MLTE and RWA domain, as well as an outline of the proactive MLTE and PBR algorithms.

2.1 IP/MPLS logical topology construction and proactive MLTE

The purpose of Multi-layer Traffic Engineering (MLTE) [5] is to extend 'classic' traffic engineering with cross-layer capabilities, using the newly found flexibility available in next-generation optical networks. MLTE achieves this objective by reconfiguring the logical topology in the IP layer and setting up and tearing down optical connections which support IP links. Apart from this logical topology construction, the MLTE strategy also has to route the offered traffic over the logical topology and of course, both routing and topology configuration are influenced by each other.

These mechanisms can be implemented and combined in various ways. For example, [2] presents an integrated routing approach across IP/MPLS and WDM layers. Multilayer routing can be done by considering a single graph model. In [3], MTLE is separated in offline logical topology design vs. online dynamic routing and capacity adjustment. A straightforward approach [4] establishes high- and low-traffic water marks to reconfigure the logical topology.

The original goal of the proactive MLTE algorithm [5] was to be able to cope with rapidly varying traffic demands; therefore, we tried to keep a distributed and online architecture. This excluded TE techniques based on e.g., integer linear programming solving which are usually better suited to offline computation—although they may deliver some more optimal results. In order to reduce complexity of the algorithm, we opted to use simple shortest path (re)routing, with dynamic link costs, for path assignment of IP/MPLS tunnels, of which we consider a full mesh (all node pairs).

The aim of the MLTE scheme is to reduce the amount of required resources for routing a certain traffic demand. The base scenario is one ‘without’ TE, where each of the IP/MPLS tunnels is assigned a single IP/MPLS forwarding adjacency in the logical topology (i.e., an optical connection or lightpath delivered by the optical layer). This leads to sub-optimal filling, especially since actual required bandwidth can vary largely between specific node pairs, e.g., depending on time-of-day, geographical distance, etc. The MLTE strategy attempts to counter this by using a certain IP/MPLS cost function in shortest path routing, in order to groom several IP/MPLS tunnels onto one IP/MPLS forwarding adjacency (henceforward called IP/MPLS link). This reduces the logical topology from a full mesh into a sparser mesh structure.

In Fig. 1, some sample IP/MPLS cost functions [5] are shown, as they are used in the MLTE scheme. The cost function is based on IP/MPLS load, which means this load needs to be measured and updated regularly; however, full information of the route of each LSP is not required. The interesting part of the function is the high cost for IP/MPLS links with a load below a certain LLT (Low Load Threshold). This, in combination with shortest path routing, avoids routing (grooming) traffic on links with a low load, leading to a general reduction in the number of links with a low load. This in turn leads to an actual reduction of the logical topology, and better filling of lightpaths.

The high load threshold (HLT) parameter further prevents overloading IP/MPLS links. The ratio low moderate ratio (LMR) between low cost (LC) and moderate cost (MC) acts as a limit to the hop length of non-direct IP/MPLS paths. The cost functions are constructed from exponential functions; however, piece-wise linear approximation can be used if necessary.

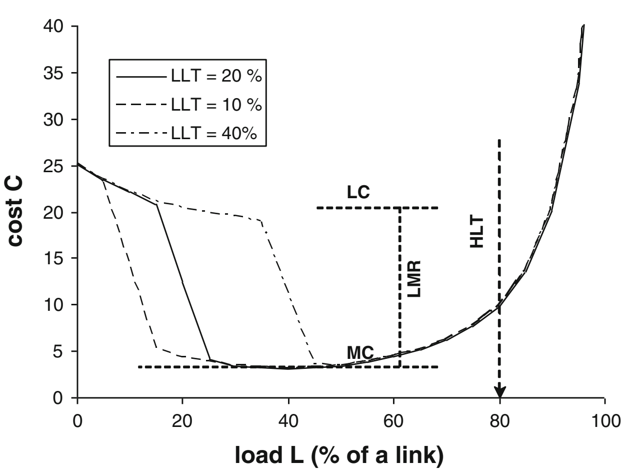

Fig. 1 IP/MPLS layer load-based cost function

In this scheme, only established IP/MPLS links have a load that can be measured. IP/MPLS links that are not established are however still considered in the routing step (which always uses a virtual full mesh), and they are assigned a load of 0%. These non-established links may be assigned an additional set up cost, in order to both reduce the number of lightpath setup/teardown events, and add some form of ‘inertia’ into the MLTE scheme, which benefits network stability as a whole.

We also presented some measures that can be taken to optimize this scheme more toward the underlying optical layer [6]. As presented in the figure above, no such measures are included yet since the cost function is still based entirely on IP/MPLS information. This means that a lightpath connecting two neighboring nodes has the same routing cost as a very long lightpath spanning the entire network. Optical layer optimization means adjusting the logical topology slightly to more closely resemble the underlying physical layer topology. The work presented earlier showed that an optical metric (which is multiplied with the original IP/MPLS cost function) allows bringing these considerations into the MLTE scheme, and even continuously setting the amount of optimization through a parameter. In this article, we will explore new types of optical metrics based on optical layer RWA interaction.

Also in [7], we extended the scenario so that IP/MPLS tunnels could be groomed into multiple parallel IP/MPLS links. A requirement for this extension was that, in addition to the routing and logical topology part of the MLTE scheme, we also added a mechanism which added or removed parallel lightpaths to or from an IP/MPLS forwarding adjacency, e.g., through techniques similar to virtual concatenation, link capacity adjustment scheme, etc. It is this last capacity adjustment mechanism (or rather, the adaptation of traffic patterns with flows larger than a single lightpath could deliver), that causes the time-correlated bursts of lightpath arrivals. With these bursty optical connection arrival characteristics, the network performance becomes more dependent on the accuracy of network state information and the subsequent problems with routing inaccuracy in RWA turn up. This routing inaccuracy problem as described in [14] concerns the impact on global network performance when taking RWA decisions according to inaccurate (or outdated) routing information.

2.2 RWA and prediction based routing

As we stated before, the MLTE strategy requires some sort of RWA mechanism in the optical layer. The RWA problem is often tackled by splitting it into two different sub-problems, the routing sub-problem and the wavelength assignment sub-problem. There are several algorithms in recent literature addressing the route selection and the wavelength assignment as independent sub-problems. A significant collection of them can be found in [9]. There are also many proposals dealing jointly with both the route selection and the wavelength assignment as a single problem. As an example, we point out the least-loaded routing (LLR) [10] and the weighted least-congestion routing first-fit (WLCR-FF) [11].

As stated above, one of the ASON recommendations focuses on RWA solutions based on distributed adaptive source routing. Most of the adaptive RWA algorithms assume that the network state databases contain accurate network state information. Unfortunately, when this information is not accurate enough, the routing decisions taken at the source nodes may be performed incorrectly hence producing a significant increase in connection blocking due to routing inaccuracy. In highly dynamic networks, inaccuracy arises mainly due to the restriction to aggregate routing information in the update messages, the frequency of updating the network state databases and the latency associated with the flooding process. It is worth noting that the first two factors attempt to reduce the signaling overhead.

The most recent studies dealing with the routing inaccuracy problem can be found in [12–21]. The contributions in [12–15] evaluate the impact on the blocking probability because of selecting lightpaths under inaccurate routing information. The proposed analytical models and the presented simulation results show that the blocking ratio increases in a fixed topology when routing is done under inaccurate information. To counteract this blocking effect, new RWA algorithms, able to tolerate inaccurate network state information have been proposed in [16–19].

In [20] and [21], we proposed the prediction-based routing (PBR) mechanism facing not only the routing inaccuracy problem but also the signaling overhead problem based on prediction concepts. The main idea is based on extending the concepts of branch prediction used in computer architecture [22]. In short, the PBR mechanism is based on predicting the lightpath, that is, the selected route and the assigned wavelength between a source-destination node pair, according to the routing information obtained in previous connection set-up actions. Thus, the PBR does not need the inaccurate network state information on the source nodes to compute lightpaths, therefore removing the frequent update messages flooding and so reducing the global network signaling. The main objective of the PBR mechanism is to optimize routing decisions not using the network state information but taking into account the history of each path.

The PBR considers one wavelength register (WR) and a prediction table (PT) for every combination of an optical route (from a set of pre-calculated paths for each source-destination pair) and wavelength (determined by WDM capabilities). The wavelength registers keep the history of the previous occupation on those lightpaths and are used as a pattern of behavior. The WRs are modified every unit of time, defined as the value we use to measure simulated time, which will include holding time, arrival time, and updating time. Each WR is updated with a 0 value when this path-wavelength combination is used for that unit of time. Otherwise, the register for unused combinations is updated with a 1. They are used to both train and access new tables named Prediction Tables.

These Prediction Tables keep track of whether previous connection requests on a path-wavelength combination, for a specific history of that combination, were blocked or not, and this by means of saturating counters (i.e., when a counter reaches its maximum/minimum, its value cannot be increased/decreased any further). A rejected connection increases the counter, an accepted one decreases it. The final selection of paths and wavelengths for an incoming lightpath request is done only taking into account this counter value and the output link availability. Thus, the PBR mechanism does not need update messages with global network state to perform RWA. Authors in [22] show that a two-bit counter gives better accuracy than a one-bit counter and the use of counters larger than two bits does not give better results. According to this, the counters are two-bit saturating, where $[00]_2 = 0$ and $[01]_2 = 1$ predict path/wavelength availability and $[10]_2 = 2$ and $[11]_2 = 3$ correspond to unavailability [20].

Figure 2 shows an example of the PBR operation in finding a path-wavelength combination for a connection arrival. Assuming two pre-calculated paths and two wavelengths over one fiber per path, a total of $2 \times 2 \times 1$ of WRs are required. In the example, two bits of history are stored in the WR; these bits index into the PTs; therefore, the PTs need four (2^2) entries. In the example, the PT of [path 0–wavelength 0] is accessed by means of the WR with value of $0|1$; the second position of the PT is accessed and the two-bit counter is read. The read value is $[00]_2$ which means that the lightpath is available. However, assume in this example that all output wavelengths toward path 0 are unavailable. This excludes all path 0 combination and therefore, the second path (path 1) is checked, starting with wavelength 0. By means of the WR of [path 1–wavelength 0] with value $1|1$, the last position of the PT is accessed. The two-bit counter is $[10]_2$, so the path-wavelength combination is predicted to be unavailable and consequently ignored. Finally, the indexed PT counter for [path 1–wavelength 1] has a value of $[01]_2$ predicting lightpath availability. Since in addition there is output link availability, this combination is selected. Assuming furthermore that the connection can be established without blocking, the two-bit counter for [path 1–wavelength 1] is updated by decreasing it to $[00]_2$.

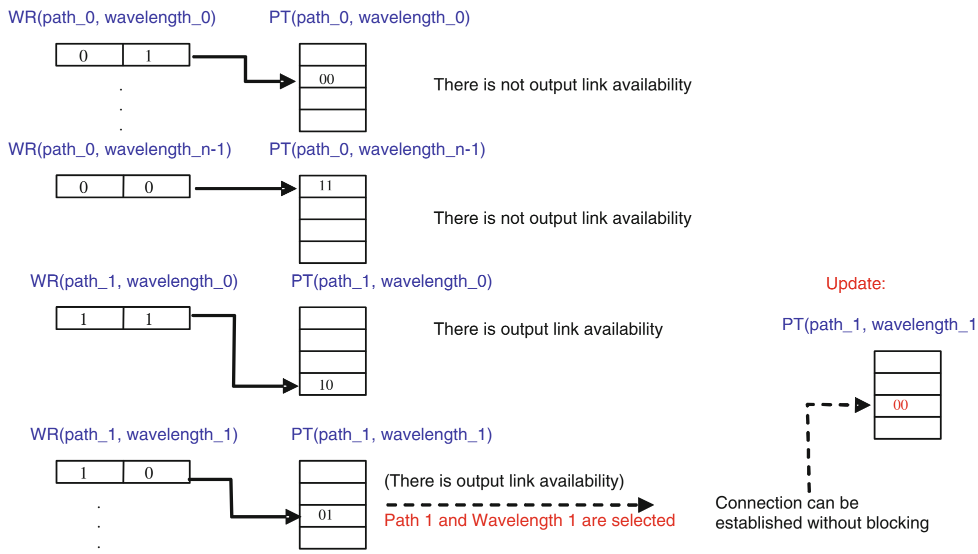

Fig. 2 Example of the PBR mechanism

3 Integration of PBR and proactive MLTE

3.1 Scheme integration

The original MLTE scheme presented in [5] uses shortest path first routing (SP) in the optical layer. This means that an optical connection between two optical nodes/IP routers has a fixed path and there is no wavelength assignment. Moreover, the original MLTE scheme does not consider the possibility of blocking in the optical layer of the required optical connections. The MLTE scheme considered that the number of wavelengths in every path of the physical topology is unlimited. These assumptions did allow minimizing total capacity usage as a performance parameter [6] using an optical metric. However, the number of blocked connections in the optical layer was not a parameter to be minimized because of the unlimited number of wavelengths.

The impact of optical layer blocking on IP/MPLS layer traffic demands was however explored in subsequent publications [7,8]. As can be expected, optical metrics were shown to influence optical layer blocking, since they optimize optical layer resource usage. However, the optical metrics in [6] were based on physical layer hop count and therefore static. If the goal is to dynamically resolve optical capacity bottlenecks, the optical metric needs to be a mechanism based on optical layer measurements, e.g., free wavelengths for each fiber.

Since the setup and teardown of a lightpath on the optical network affect the free and used capacity on multiple optical links, all node pairs with a path over these links must have their load information recalculated (re-flooded, etc.). This gives quite a lot of overhead. Also, a single recalculation involves non-trivial maximum flow problems, which leads to further difficulties if this load information is to be used in fast adapting cross-layer TE. Using the current scheme for more than one shortest path per node-pair would result in an exponential amount of maximum flow calculations each time an optical action (setup or teardown) is performed which is consequently not scalable.

Therefore, we have looked at replacing the simple SP with a PBR mechanism to reduce and in fact remove the flooding and calculation times in the optical layer. PBR is inherently not reliant on flooding; maximum flow calculation can be removed by extracting an optical metric directly from the PBR wavelength registers and prediction tables, using linear transforms.

Additionally, under the capacity adjustment mechanism [7], an IP/MPLS link has a dynamic capacity, e.g., this capacity can be 1 up to 16 optical connections, which means that every new bandwidth request in the IP layer can cause up to 16 optical connection requests in the optical layer of the MLTE scheme. With these bursty optical connection arrival characteristics, the performance in terms of blocking probability becomes more dependent on the updating frequency when using typical RWA which needs flooding of the network state information. Now, one bandwidth request in a node in the IP layer, and the corresponding establishment imply a lot of reconfigurations (setup of a lot of lightpaths) in the optical layer, and thus a lot of signaling overhead. Also from this viewpoint, it would be appropriate to use mechanisms independent of the flooding of network state information such as the PBR.

Figure 3 outlines how the PBR and MLTE schemes are integrated. Incoming IP traffic requests are offered to the MLTE strategy which uses the above-mentioned cost function and optical metric to construct a logical topology in

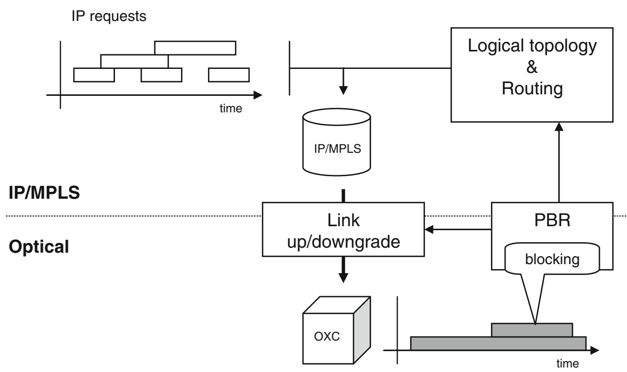

Fig. 3 MLTE and PBR integration outline

the IP/MPLS layer. As traffic load changes over time, the logical topology reconfiguration and rerouting mechanisms will adapt to these changes. IP/MPLS link up/downgrade is a low-level mechanism which does not offer cross-layer optimization and will often lead to sub-optimal lightpath capacity filling. However, it can cope with fast traffic shifts where rerouting and especially logical topology are limited in response rate.

3.2 PBR-based optical metrics

Blocking in the optical layer will cause the related IP traffic requests to be refused as well. There is no direct feedback into the MLTE scheme TE database, as IP traffic refusal is not used to, e.g., route traffic around network bottlenecks which could be defined using blocking information. Instead, the integrated scheme relies directly on the PBR-based optical metric. Keeping track of traffic blocking would introduce additional state information in the TE database; also, it would only shift the maximum flow problem from the optical to the IP/MPLS layer. In the end, the objective remains to calculate some kind of load metric in the optical layer; this can be done more directly from information extracted from the PBR scheme. PBR-based optical metrics can be reported from the optical layer in the same way as static metrics; no additional network state must be stored. However, as they are created dynamically based on PBR register and table data, they should be updated regularly (whereas static metric would only be exchanged during network initialization).

Optical metrics assign a cost to each optical node pair, just like the IP/MPLS load-based cost function assigns a cost to each node pair in the IP/MPLS full mesh topology abstraction. The product of both costs is used in reducing the full mesh using the MLTE scheme. The optical metrics examined are based on total apparent load from the PBR mechanism. This apparent load is the rate of predicted number of unavailable paths vs. total available paths. For example, for the Fig. 2, this apparent load is 0.25, as only one out of four path-wavelength combinations is available—remember that path 0 has no output link availability and [path 1–wavelength 0] has a PT counter predicting unavailability. For the PBR RWA algorithm, an apparent load can be calculated for each optical node pair. This load will change as connections are set up or torn down (PT change) and also as the network shifts into the next time unit (WR history change). These updates however are performed completely locally in the equipment storing the PBR data structures. The per-node pair apparent load is indicated as $L_{\text{PBR}}(s, d)$ for a source destination pair $s - d$.

The end goal of this work is to demonstrate the merits of PBR-based optical metrics, and prove their MLTE performance to be similar to, or better than static metrics. The reference static metric M_{static} is based on the shortest path hop count hops(s, d) between those nodes s and d. The metric is a linear function of hop count [6]:

$$M_{\text{static}}(s, d) = S.\text{hops}(s, d) + C \tag{1}$$

The optimization parameter C is a fixed cost for a 'zero-hop' lightpath (basically, a fixed setup cost for a lightpath). We chose $S = 1 - C$ so that, independent of this parameter C, all metrics yield a cost 1 for a 1-hop lightpath.

Decreasing the optimization parameter C allows concentrating more toward optical layer optimization (point-to-point grooming), at the cost of increased IP/MPLS router load (total router traffic).

We have looked at two types of optical metrics based on such PBR-based optical apparent load, using the same scheme with parameters S and C. The PBR apparent load-based metrics are:

1) PBR adjusted metric

Optical metrics similar to the static metric (hop-count based); however, with the static optimization parameter set according to the PBR apparent load (on a per-node basis). The hop-count-based metric M_{adjusted} with PBR-adjusted optimization parameter is computed:

$$M_{\text{adjusted}}(s, d) = (S + L_{\text{PBR}}(s, d)).\text{hops}(s, d) + (1 - S - L_{\text{PBR}}(s, d)) \tag{2}$$

For M_{adjusted}, S has been replaced with $(S + L_{\text{PBR}})$, which is no longer static. It should be noted that now C is also dynamically adjusted to join with $(S + L_{\text{PBR}})$. While operators have to adjust S for the static case, here information exposed from the PBR data structures performs the adjustment automatically. Specifically, when optical load becomes higher at certain optical node pairs, point-to-point grooming will be encouraged at those nodes, saving optical capacity.

2) PBR apparent load metric

Optical metrics-based entirely on the apparent load, not including any physical hop-count or other static network characteristics. The pure PBR apparent load metric M_{PBR} is computed as follows:

$$M_{\text{PBR}}(s, d) = S_{\text{PBR}}.L_{\text{PBR}}(s, d) + (1 - S_{\text{PBR}}) \tag{3}$$

In this case, hop count has been completely eliminated from the metric, and replaced with the apparent load L_{PBR}. In other words, we hope that the apparent load can represent physical layer topology in the same way as a static hop count. In fact, we hope it will do better, since physical layer is of course static, cannot adapt to traffic patterns, and may actually be unsuitable for certain patterns.

4 Case study and simulation results

In order to validate the new integrated IP/MPLS and RWA algorithms which utilize limited availability information, and the presented PBR-based metrics M_{adjusted} and M_{PBR}, we present some simulation results. First of all, we study the IP request blocking rate versus the average node pair traffic for the optical static metric, for the PBR-adjusted metric and for the PBR apparent load metric, ranging the S and S_{PBR} parameters. Then, we present results for the IP/MPLS router load versus the average node pair traffic for the PBR apparent load metrics.

The characteristics of the simulation are the following: the simulation uses the 14-node NSFNET-based network shown in Fig. 4, which has 21 fiber links, some of which are long-haul. We assumed 8 wavelengths per fiber (no wavelength translation in the PBR RWA).

In the following results, we examine IP request traffic patterns with a uniformly distributed bulk node pair average traffic. We use a grooming factor of 20 for the bandwidth of the IP requests vs. lightpath bandwidth (e.g., one IP request: 500 Mbit/s vs. lightpath bandwidth: 10 Gbit/s). The uniformly distributed bulk parameter is adjusted every 100 time units. This bulk parameter is used in modulating a per-node pair traffic generator modeling IP/MPLS traffic arrivals and holding times as Poisson processes. This yields a sequence of traffic requests with a node pair demand which remains fairly stable for a period of 100 time units.

The MLTE strategy performs IP/MPLS logical topology updates and MPLS LSP traffic flow reroutes 16 times during each of these 100 time unit periods, while the Poisson traffic generator modifies traffic loads slightly. The presented performance metrics were sampled at 2 time points for each interval (taking into account periods of network state convergence), or otherwise averaged over the entire simulated time. We simulated 250 traffic periods for each scenario, in order to compare these performance metrics against network load.

Figure 5 shows some example IP request blocking rates versus average offered node pair traffic for the hop-count optical metric with PBR apparent load-adjusted optimization parameter, PBR- adjusted metric. It turns out that this type of metric is fairly independent of the parameter S. Indeed, adding the apparent load into the linear hop-count function will optimize very strongly toward the optical layer, L_{PBR} complementing the static S where necessary.

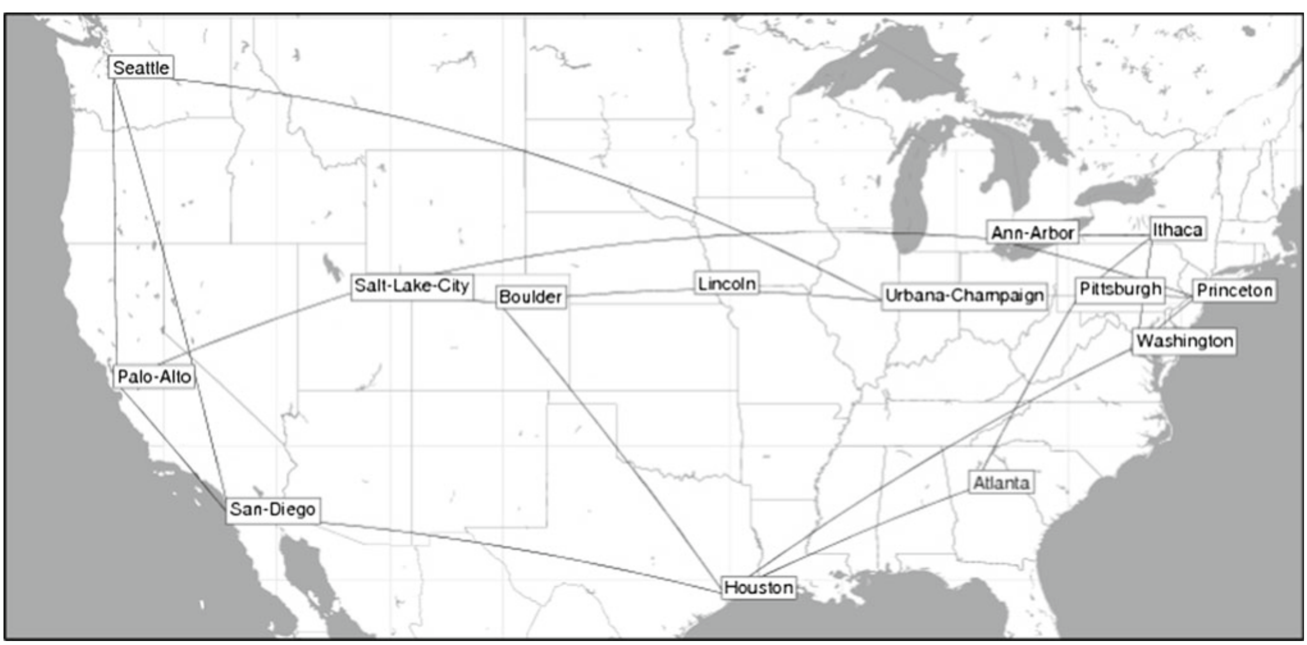

Fig. 4 14-node reference network

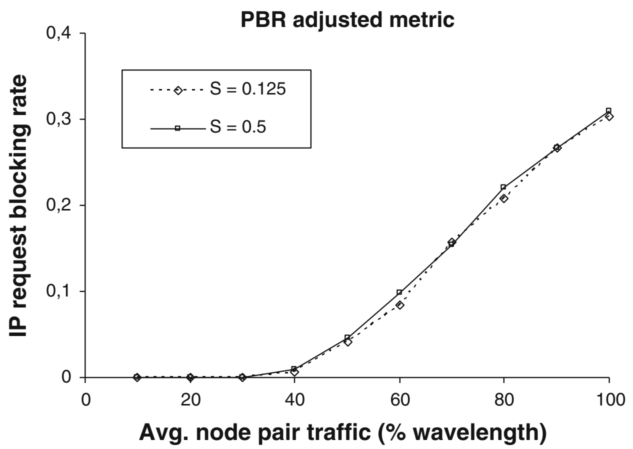

Fig. 5 PBR adjusted hop-count metric; example blocking rates

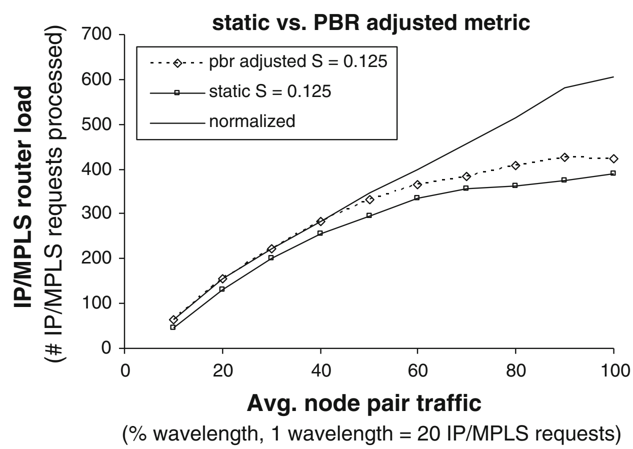

Fig. 7 Static versus PBR adjusted metric; IP/MPLS router loads

We can compare the old static metric against the PBR-adjusted metric as shown in Fig. 6. The PBR-adjusted metric optimizes more toward the optical layer as total traffic volume grows. Blocking rates are clearly correspondingly lower for the PBR-adjusted metric as average node pair traffic grows.

However, as with the static metrics, stronger optical optimization will increase IP/MPLS router load (expressed as total process IP/MPLS traffic volume at a node), since a compromise needs to be made between optical and IP/MPLS layer optimization.

In Fig. 7, we indicate average IP/MPLS router load vs. average node pair traffic volume (in percentage of wavelengths, which each fit 20 requests). The adjusted metric shows slightly higher loads (but note that the relative blocking rate reduction is higher). We also indicate, for the PBR-adjusted case, router load normalized with blocking rate (load × [1–blocking rate]), since for increasing IP request blocking, we will see router load saturating for high traffic volumes, as the optical layer becomes a bottleneck.

However, as noted in [6], there is a limit to the amount of optimization that can be set by adjusting the optimization parameter of the metric. Beyond certain values, the optical metric will conflict with the IP cost function and break down the cost penalty for lightly loaded IP/MPLS links. This interferes with logical topology generation. This in fact may also explain the relative independence from S in Fig. 5 for the PBR-adjusted metric (full optimization range is reached by the PBR adjusting).

When removing the hop-count values from the metric (as is done with the PBR apparent load metric) however, we can pinpoint problem areas in the network, and only have the optical metric set an increased cost there. Also, the probability of an IP/MPLS cost function conflict is much lower since the optical optimization acts on a smaller part of the topology.

Figures 8 and 9 show results for this pure PBR apparent load metric for different S_{PBR}, pointing out the correct working and the adjustability of a topology-independent optical

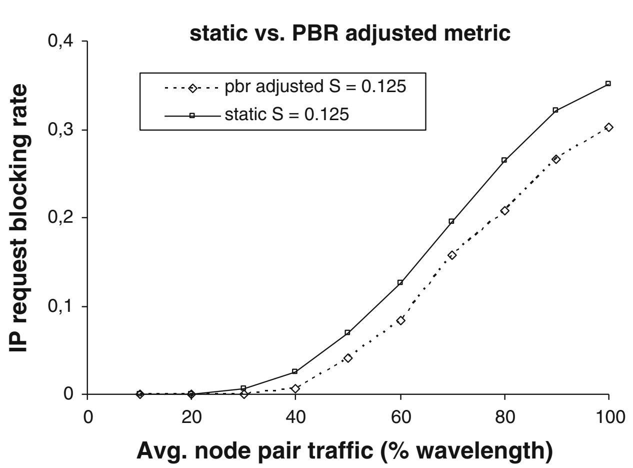

Fig. 6 Static versus PBR adjusted metric for $S = 0.125$

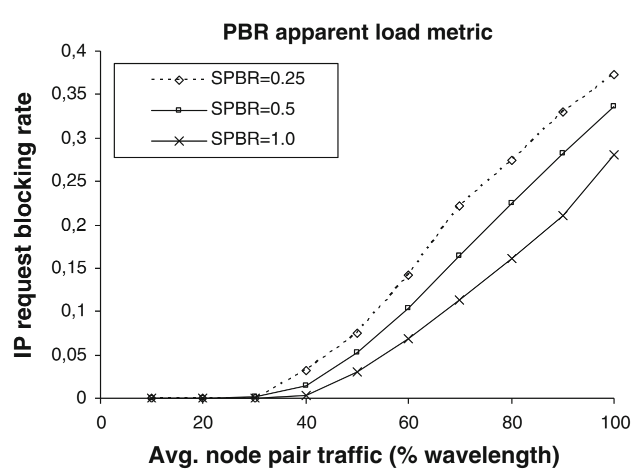

Fig. 8 PBR apparent load metric, blocking rates

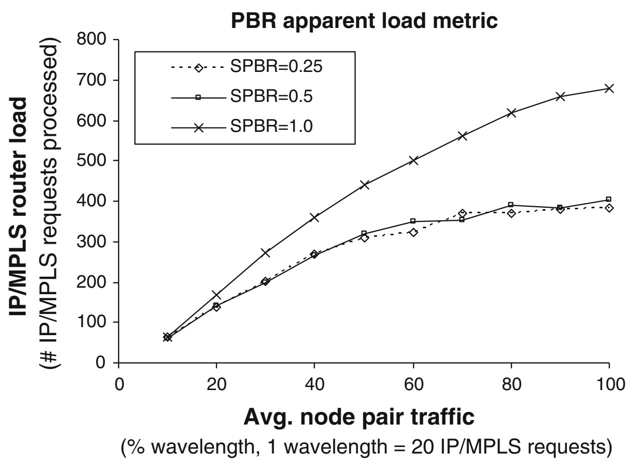

Fig. 9 PBR apparent load metric, router load

metric. Metrics with $S_{\mathrm{PBR}} = 0.25$ achieve similar blocking rates to the PBR-adjusted metrics (shown on Fig. 5). Higher S_{PBR} allows delaying IP/MPLS request blocking toward higher traffic volumes.

The bottom part of the figure shows the non-normalized average IP/MPLS router loads, which for low S_{PBR} yield similar results from the PBR-adjusted simulations. For high optical layer optimization, the very thorough optical layer optimizations and resulting point-to-point grooming increase IP/MPLS layer load. From Fig. 8, we can deduct S_{PBR} dependent behavior. This means that now with the introduction of the full PBR apparent load metric, optical layer operators have regained the optimization parameter mechanism (S_{PBR}) which was lost with the PBR-adjusted metric (as the settable S there had only minor influence on IP/MPLS vs. optical layer optimization).

This pure PBR apparent load-based metric allows setting a high optimization toward blocking of traffic requests more safely, since such optimization remains limited to those points in the network with high network loads. This way, there is no interference with normal logical topology construction and IP/MPLS routing.

Additionally, the optical topology typically determines the nodes that will see a high optical load (i.e., nodes in the 'core'-part of the network). The pure PBR apparent load-based metric will export these points with high loads also to the IP/MPLS layer. This means that the set of nodes requiring higher capacity OXCs and IP/MPLS routers will be more closely defined, which benefits network dimensioning.

Lastly, the pure PBR apparent load-based metric shows that an optical metric based solely on (perceived) optical load is possible, and that there is no requirement to rely on optical topology knowledge in exporting such a metric to a higher (IP/MPLS) layer.

5 Summary and conclusions

The work in this article is based on implementing IP/MPLS and PBR algorithms which take limited availability of information into account in a MLTE strategy, reducing the need for frequently updated network state information which causes large signaling overhead in complex multilayer networks. Optical metrics allow integrating IP/MPLS and RWA algorithms. In earlier work, such metrics were based on static network information. With the PBR mechanism, however, dynamic metrics can be constructed taking into account optical layer load information.

From the obtained results, we can conclude that such metrics perform similar to the static metrics from earlier work. Moreover, the PBR apparent load type of metric specifically does not require extensive up-front configuration (such as physical layer topology information), but instead is based solely on state information collected from the PBR structures at run-time. This pure PBR apparent load-based metric allows for more localized and therefore more efficient optimization toward optical layer performance. The localized nature also leads to a more easily predictable capacity distribution in the optical layer, which benefits network dimensioning.

We can conclude that the high adaptability of both the IP/MPLS MLTE and optical layer PBR mechanisms proved to be complementary and instrumental in providing a more robust and efficient multilayer traffic engineering approach for IP/MPLS over optical networks.

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Mario Pickavet received an M.Sc. and Ph.D. degree in electrical engineering, specialized in telecommunications, from Ghent University in 1996 and 1999, respectively. Since 2000, he is professor at Ghent University where he is teaching telecommunication networks and algorithm design. His current research interests are related to broadband communication networks (WDM, IP, (G-)MPLS, OPS, OBS) and include design, long-term planning and routing of core and access networks. Special attention goes to Operations Research techniques that can be applied for routing and network design. He has published over 150 international journal and conference papers in this field.

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