Leveraging Multipath Routing and Traffic Grooming for an Efficient Load Balancing in Optical Networks

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***Abstract*— Optical networks can benefit from multipath routing by routing traffic over diverse fiber links to fulfill bandwidth requirements, balance network load and improve resource utilization. This paper focuses on the effectiveness of multipath routing on aggregating residual bandwidth of the established lightpaths using dynamic traffic grooming. An optimization model based on Integer Linear Programing (ILP) is formulated to leverage multipath routing and grooming to serve connection requests with known duration, in a scenario where the dynamic traffic can demand bandwidth either larger or smaller than a single wavelength capacity. The impact of a balancing policy, referred to as Holding Time Balancing (HTBalancing), on multipath routing with traffic grooming in optical networks is also investigated. Numerical results show that the proposed optimization model can achieve a lower bandwidth blocking and a better load balancing with HTBalancing policy, when compared with single path routing. The proposed relaxation algorithm can effectively find near optimal solutions, and be applied in realistic scenarios.**

I. Introduction

Dynamic traffic grooming can be utilized in combination with multipath routing to serve the bandwidth intensive applications when resource is not sufficient in the optical network. At the same time, most of the connections require bandwidth smaller than the capacity available in a wavelength, leading to low resource utilization of established lightpaths. Leveraging multipath routing and dynamic grooming can efficiently utilize the residual capacity of the under-used wavelengths. This idea, however, is especially feasible in operational optical networks where the duration of the connections is known (as it is typically the case) [1] [2] [3]. More so than when the connection duration is unknown, with the known connection duration, we can optimally select a set of existing lightpaths to serve new connection request with traffic grooming, and release the resources allocated to a lightpath at the lowest possible time [1].

This paper investigates the effectiveness of combining multipath routing and dynamic traffic grooming on serving connections with known duration. The goal is to address the question of whether the optical networks can optimally benefit from traffic grooming into multiple existing lightpaths to achieve lower blocking and better load balancing. To this end, an optimization model based on Integer Linear Programing (ILP) is proposed, and moreover, an approximated algorithm based on linear relaxation technique is employed to reduce the time to solve the ILP. The latter has been shown highly beneficial in dynamic environments where time reduction of ILP solver is critical to the algorithm practical applications. To further investigate the impact of holding time awareness on the proposed multipath based traffic grooming approach, we apply a holding-time aware algorithm proposed in our previous work [2], referred to as HTBalancing policy, on the optimization model presented in this paper. Numerical results indicate that by balancing the load among multiple routes with dynamic grooming, the bandwidth blocking as well as network cost are reduced. With HTBalancing policy, a fair distribution of resources among source-destination pairs is achieved, even with the differential delay constraints.

This paper is organized as follows. Section II gives an overview of related work. Section III presents the motivation for using holding time information in multipath routing. Section IV introduces the ILP formulation to balances the load on multipath and on singlepath routes, by the employment of the HTBalancing policy. Section V presents a numerical evaluation of the proposed algorithms. Finally, Section VI concludes the paper.

II. Related Work

Multipath routing has been proposed to cope with the high bandwidth demands of applications which requires bandwidth larger than the capacity of one wavelength [4]. In [5], multipath routing was applied in Carrier Ethernet Networks with multi-domains and schemes referred as *end-to-end multipath routing* and *per-domain multipath routing* were introduced. Moreover, the benefits of multipath routing in multi-domain networks and the cost of the multipath routing as a function of buffering requirements were assessed.

Information on the duration of the connections was employed in [1] to make decisions on grooming traffic with the aim of early release of lightpaths. In our earlier work, [2] we proposed an algorithm, referred as HTBalancing, which balances the network load among existing lightpaths considering the duration of the requests. In this paper, we extend this work to show how the HTBalancing policy can impact dynamic traffic grooming based on multipath routing, especially in scenarios with highly demanding requests for bandwidth.

III. Use of information on connection duration in grooming

The HTBalancing algorithm is motivated by two main factors. On one hand, utilizing established lightpaths is cheaper than creating a new lightpath. Therefore, the optical networks can benefit from the overlap between the lifetime of established lightpath and the incoming connection holding time to save cost and improve resource utilization. On the other hand, lightpaths with large residual bandwidth is more favorable in traffic grooming, which shall be defined with low cost in the selection of lightpaths for traffic grooming. Therefore, the HTBalancing algorithm defines the cost functions for lightpaths of different kind as follows [2]:

$$C(p_i) = (c\_ht(p_i) \times \alpha) + \left(\frac{1}{bw(p_i)} \times (1-\alpha)\right) \quad (1)$$

$$c\_ht(p_i) = \begin{cases} hp_i \times \epsilon & \text{if } L_i \geq H \\ hp_i \times \epsilon + hp_i \times \Delta_t & \text{if } L_i < H \\ hp_i \times H & \text{if new path} \end{cases} \quad (2)$$

where:

- $C(p_i)$ is the cost utilization of the lightpath p_i;
- $c\_ht(p_i)$ is the holding-time contribution to the cost of the i^{th} lightpath (Eq. 2);
- α determines the weight used for the holding-time cost function;
- bw is the available bandwidth in p_i;
- $(1-\alpha)$ determines the bandwidth availability's weight;
- H is the holding-time of the request;
- L_i is the lifetime of i^{th} lightpath;
- $\Delta_t = H - L_i$;
- $\epsilon = 10^{-5}$ is a small constant;
- hp_i is the number of hops along the i^{th} lightpath.

The term $\frac{1}{bw(p_i)}$ in Equation 1 is replaced by 1 for lightpaths yet to be established to avoid unnecessary establishment of lightpaths.

IV. Grooming based on multipath routing

The algorithms proposed in this section aim to optimally select multiple existing lightpaths for traffic grooming with holding time awareness. The selection of lightpaths is based on the HTBalancing strategy presented in Sec. III. The proposed model is designed to provide optimal solutions for both high bandwidth demanding requests as well as low bandwidth demanding requests. It chooses lightpaths for traffic grooming, on which will have the smallest enlargement of its lifetime after the groom of the request. A formulation of the problem of balanced traffic grooming based on singlepath routing is also presented for the assessment of the proposed method.

A. Multipath Formulation

The description of the WDM network used as the input to the ILP formulation is given by a graph $G(V, E)$, where V is the set of nodes and E the set of fiber links. A capacity $c_{i,j}$ is associated to each link $e \in E$, given by the number of available wavelengths in the fiber link, denoted by $W_{i,j}$. A loop free path p in G is defined as a list of nodes (s,v_1,...,v_n,d), where s and d are the source and destination, respectively. s, d, $v_i \in V$ and (s,v_i), (v_i,v_{i+1}), (v_n,d) $\in E$. Furthermore, the virtual topology is given as input to the ILP. The virtual topology describes the already established lightpaths and their available bandwidth.

The proposed algorithm tries to find multiple routes (multipaths) to provide a requested connection at a minimum cost. The cost considers the connection duration and the bandwidth availability of the lightpath as presented in Section III. To formulate the ILP, the following variables are defined:

- $F_{p,i,j,w} \in \{0, 1\}$: if the wavelength w in the link i, j is used by the path p, this value is one; otherwise it is zero;
- $X_{p/lp,w} \in \{0, 1\}$: if the wavelength w is used by a lightpath, this value is one; otherwise it is zero. The lightpath can be a new lightpath p or an already established lightpath lp;
- C_{lp}: the cost of an already established lightpath lp, defined by Equation 1;
- B_{lp}: represents the available bandwidth in the already established lightpath lp;
- R: gives the bandwidth demand of a call, i.e the carrier required (the value 3 means the carrier OC-3; the value 12 means the carrier OC-12; ...);
- H: gives the connection duration/holding-time;
- λ: gives the wavelength capacity;
- $\alpha = 0.5$: a constant used to calculate the cost of a lightpath to be established according to [2];
- P : is the set of lightpaths (p and lp) used to calculate the solution.

The algorithm for balancing the aggregated traffic among multiple routes is formulated as following:

$$Min \sum_{lp,w} X_{lp,w} \times C_{lp} + \sum_{p,w} \left(X_{p,w} \times (1-\alpha) + \sum_{i,j} F_{p,i,j,w} \times H \times \alpha \right) \quad (3)$$

$$\sum_i F_{p,i,j,w} - \sum_k F_{p,j,k,w} = \begin{cases} -X_{p,w} & \text{if } j = s \\ X_{p,w} & \text{if } j = d \\ 0 & \text{otherwise} \end{cases} \quad \forall j, w, p \quad (4)$$

$$\sum_{lp,w} X_{lp,w} \times B_{lp} + \sum_{p,w} X_{p,w} \times \lambda \geq R \quad (5)$$

p and $lp \in P$; $w = [1, 2, ...W_{i,j}]$, $i, j \in E$.

The objective function (Eq. (3)) tries to find paths between source s and destination d that have minimum cost. The utilization cost of a lightpath is based on the connection holding-time and the available bandwidth. The first term of the objective function considers the already established lightpaths, which cost is defined by Eq. (1) and which are given as input to the problem. The second term of Eq. (3) takes into account the cost of new paths. According to the HTBalancing algorithm, $\frac{1}{bw}$ in Eq. (1) is replaced by 1 and $c\_ht(p_i)$ is given by the value of the third option in Eq. (2), i.e $c\_ht(p_i) = hp_i \times H$. Therefore, the cost of each new lightpath is given by $C(p_i) = ((1-\alpha) + (hp_i \times H \times \alpha))$. Note that the number of hops hp_i is computed by the summation of $F_{p,i,j,w}$ over the indexes i and j.

The wavelength continuity is guaranteed by the index w in all variables. The flow conservation constraint (Eq. 4) assures that the incoming data is equal to the outgoing data for all nodes selected to establish the lightpath s-d. Equation

(5) defines the capacity constraint, i.e the sum of available bandwidth in the already established lightpaths (first term) plus that in the lightpaths suggested to be created (second term) must be greater or equal to the bandwidth requested (R) by the incoming connection.

B. Singlepath Formulation

To assess the advantage of employing load balanced multipath in dynamic traffic grooming, a singlepath formulation of the problem is defined. Note that singlepath as used here refers to the route which can accommodate several lightpaths established to satisfy the bandwidth demands larger than one wavelength. The variables used are:

- $F_{i,j,w} \in \{0, 1\}$: if wavelength w in the link i, j is used, this variable is one. Otherwise, it is zero;
- $T_w \in \{0, 1\}$: if the wavelength w is used in the solution, this value is one; otherwise it is zero;
- $X_{lp} \in \{0, 1\}$: if the already established route lp is used in the solution, this value is one; otherwise it is zero;
- C_{lp}: the cost of the already established route lp;
- B_{lp}: the available bandwidth in the already established route lp;
- Θ: the number of wavelengths necessary (R/λ) to meet a requested demand;
- R, H, λ and α are defined in Section IV-A.

$$Min \sum_{lp} X_{lp} \times C_{lp} + \sum_{w} \Big(T_w \times (1 - \alpha) + \sum_{i,j} F_{i,j,w} \times H \times \alpha \Big) \quad (6)$$

$$\sum_{i} F_{i,j,w} - \sum_{k} F_{j,k,w} = \begin{cases} -T_w & \text{if } j = s \\ T_w & \text{if } j = d \\ 0 & \text{otherwise} \end{cases} \quad \forall j, w \quad (7)$$

$$\sum_{lp} X_{lp} \leq 1 \quad (8)$$

$$\sum_{lp} X_{lp} \times B_{lp} \geq \sum_{lp} X_{lp} \times R \quad (9)$$

$$\sum_{w} T_w = \Theta \times (1 - \sum_{lp} X_{lp}) \quad (10)$$

$$\sum_{w} F_{i,j,w} = \Big\{ 0, \sum_{w} T_w \Big\} \quad \forall i, j \quad (11)$$

$w = [1, 2, ...W_{i,j}]$, $i, j \in E$

The objective function (Equation (6)) finds a single route between source s and destination d with minimum cost. As in the multipath formulation, the cost of each lightpath in the route is defined using Eq. (1). The first term of Eq. (6) defines the cost of already established routes (and are given as input to the problem), while the second term denotes the cost of new potential routes. The index w in all variables ensures the wavelength continuity constraint. Flow conservation is provided by the Constraint (7). Since a singlepath solution must be found, only one of the already established route (lp) can be chosen, which is specified by Constraint (8). Furthermore, an already established route can compose the solution just in the case it has enough available bandwidth to provide the required call (Eq. (9)). Similarly, if the ILP solution determines the creation of a new route ($F_{i,j,w}$), the sum of the bandwidth in all the lightpaths must be greater or equal to the required bandwidth of the incoming request (Eq. (10)). Constraint (11) ensures that all lightpaths are established along the same route.

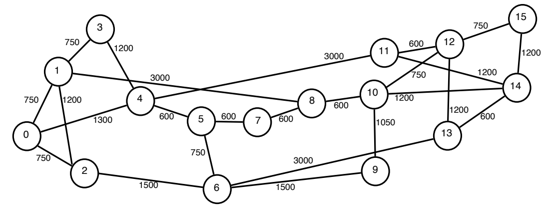

Fig. 1. NSF Topology

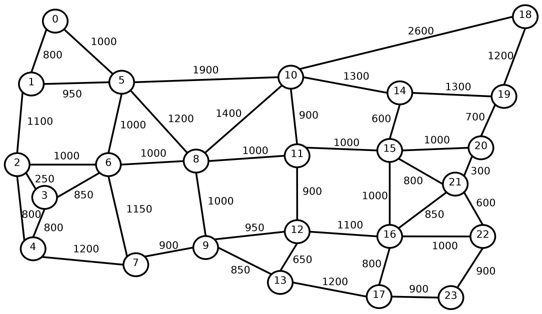

Fig. 2. USA Topology

V. Performance Evaluation

To assess the benefit of leveraging multipath routing with dynamic traffic grooming in optical networks with holding-time awareness, the multipath solutions are compared with single path solutions. The impact of HTBalancing policy on the proposed multipath based traffic grooming approach is also evaluated. The solutions are single-hop and the WDMSim [6] simulator is used in the evaluation. The independent replication method was employed to generate confidence intervals with 95% confidence level. Each simulation run involved 10.000 requests. The optimal algorithm and the relaxed algorithm have as input information on the call (s, d, B, h) and as well as on the current state of the network for each incoming request. The optimal and the relaxed algorithms were solved using the Xpress-MP Suite tool [7]. The network state for the next execution algorithm is updated whenever a request is accepted.

NSF topology, with 16 nodes and 25 bidirectional links (Fig. 1) and the USA topology, with 24 nodes and 43 bidirectional links (Fig. 2) are used in the simulation. In both topologies, it is assumed that each fiber has 16 wavelengths, with capacity of an OC-192 carrier (10 Gbps). Each node is a full grooming optical switch, with no wavelength conversion capability.

The connection demands are distributed according to the following probability distribution: $9/45$ for OC-1; $8/45$ OC-3; $7/45$ for OC-12; $6/45$ for OC-48. Requests with high bandwidth demands are distributed according to the following probability distribution: $5/45$ for OC-211; $4/45$ for OC-403; $3/45$ for OC-595; $2/45$ for OC-787; $1/45$ for OC-979.

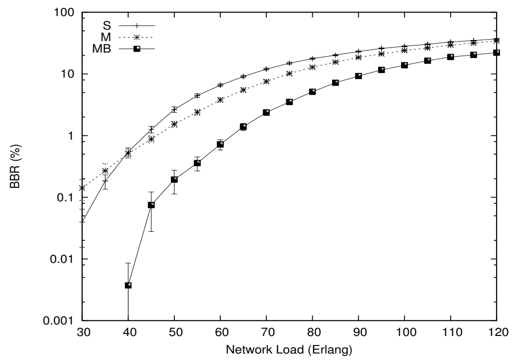

Fig. 3. BBR over the network load for NSF network

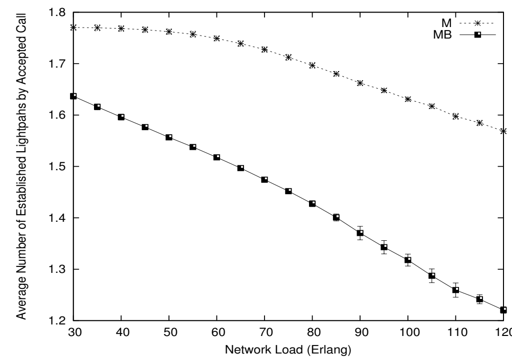

Fig. 4. Average number of used lightpaths over the network load for NSF network

Connection requests are uniformly distributed among all pairs of nodes. The holding time follows a negative exponential distribution with a mean of one unit. The network load, given in Erlang, is defined as: $A = R \times h \times (B/\lambda)$; where R is the call arrival rate, h is the call holding time, B is the call bandwidth request normalized to the value of the wavelength capacity λ.

The metrics collected in the simulations were the bandwidth blocking ratio (BBR), i.e., the percentage of the amount of blocked traffic over the total bandwidth requested and the fairness index which gives the dispersion of the BBR values among source-destination pairs. To account the cost of electronics components and signaling overhead, it was accounted the product the average number of established lightpaths by the number of accepted calls. The differential delay among the lightpaths was also accounted. In the figures, the algorithms are denoted by: S for load balanced singlepath; MB for load balanced multipath routing; M for multipath routing without load balancing.

Figure 3 presents the BBR values for the NSF topology as a function of the load. Under low loads, the solution using singlepath produces blocking while those employing load balanced multipath start blocking requests only under 40 Erlang with bandwidth blocking ratio 99% lower than that when singlepath is employed. This difference decreases to 40% under loads of 120 Erlang. Comparing load balanced multipath algorithm and multipath without load balancing, it is noticeable that the use of the residual bandwidth of existing lightpaths decreases significantly the blocking of connections. Under loads of 40 Erlang, the solution load balanced multipath generates a BBR value 99% lower than given by multipath without load balancing. Under loads of 120 Erlang, the solution with balanced load gives a BBR value 35% lower than that generated by unbalanced load. The lower connectivity of the nodes in the NSF topology implies on a lower number of alternative paths among the source destination pairs, which leads to the creation of bottlenecks even under low loads. This highlights the importance of using load balancing to maximize the chances of accepting connections.

The establishment of a lightpath as well as its tearing down imply signaling overhead. Furthermore, establishing new lightpaths increases the number of electronic equipments required to meet the demands. Figure 4 compares the average number of established lightpaths by the number of accepted calls for the NSF network. The employment of balanced load grooming reduces considerably the need for lightpath establishment. Under loads of 30 Erlang, the load balanced multipath algorithm uses 7.5% less lightpaths by accepted call than the multipath without load balancing algorithm. However, as the load increases, there are less available routes to be used by a potential solution, evincing the benefits of distributing the traffic to minimize the utilization cost. The solutions with HTBalancing algorithm utilize a smaller number of lightpaths comparing with those without HTBalancing algorithm. 15% and 22% reduction is observed under network loads of 75 Erlang and 120 Erlang, respectively, in Figure 4.

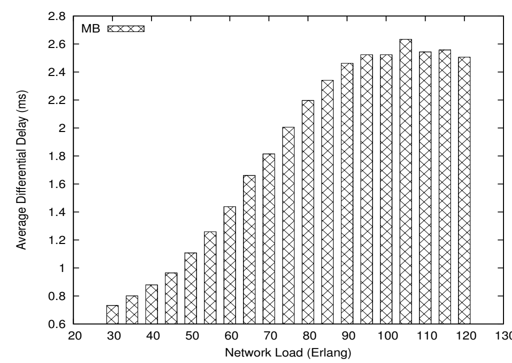

Fig. 5. Average Differential Delay of lightpaths chosen in the solutions found by grooming with multipath routing for the NSF network

Figure 5 shows the average differential delay of the lightpaths chosen in the solutions found by load balanced multipath algorithm for the NSF topology. The differential delay in the proposed algorithm is ameliorated by the selection of short routes, which is defined in the cost function (Equation 1) by considering the number of hops (hp_i) along the route. Furthermore, the distribution of the load among the links prevents delays resulting from link overload. We note that all the differential delay of all lightpaths are below $5ms$, which

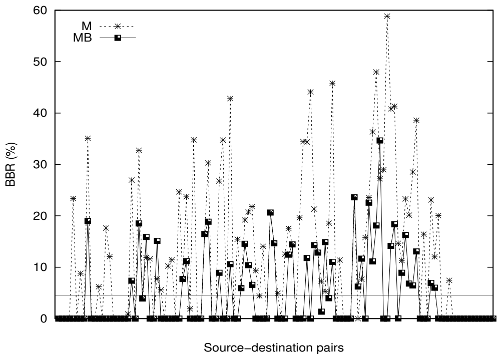

Fig. 6. BBR distribution of each source-destination pair for a load of 85 Erlang (NSF)

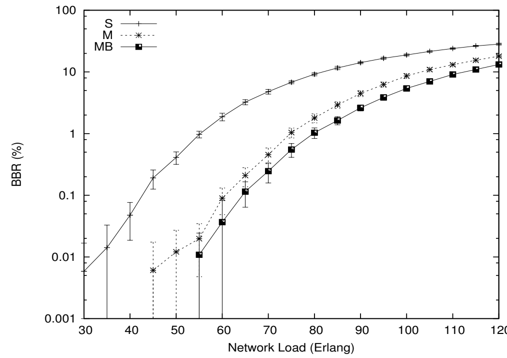

Fig. 7. BBR over the network load for USA network

is the upper limit suggested in [8]. Figure 6 shows the per pair BBR distribution and the BBR mean value for a single simulation for a load of 85 Erlang for the NSF topology. For some pairs, the multipath without load balancing algorithm produced blocking rates up to $4,7$ times greater than its mean BBR value $(12,4\%)$ and up to $12,8$ times greater than the BBR mean value $(4,5\%)$ given by load balanced multipath algorithm. This shows the importance of distributing the traffic among the routes to improve resource utilization.

Figure 7 shows the BBR values for the USA topology as a function of the load. Again under low loads, the load balanced singlepath algorithm generates blocking while those employing multipath routing start blocking requests only under loads of 40 Erlang when multipath without load balancing algorithm is employed and under 55 Erlang when load balanced multipath is employed. Under a load of 55 Erlang, the singlepath case generates BBR values 99% higher than that given by the load balanced multipath algorithm. This difference decreases to 53% under loads of 120 Erlang.

Comparing the load balanced multipath algorithm with the multipath without load balancing algorithm, we note that the use of the load balancing improves the bandwidth utilization and, as a consequence, it increases the admission of requests. Under loads of 60 Erlang, the load balanced multipath algorithm produces a BBR value 59% lower than the one given by multipath without load balancing. Such difference decreases to 44% under load of 85 Erlang. Under loads of 120 Erlang, the load balanced multipath generates BBR value 27%, which is lower than the counterparts without load balancing algorithm.

Due to space limitation besides BBR other metrics, when the USA topology is employed, are omitted in this paper. The values of these metrics leads to the same conclusions drawn when using the NSF topology.

An approximative algorithm based on Randomized Rounding technique was implemented to reduce the execution time. For the NSF topology, the relaxed algorithm time reduction were up to $14,0\%$. The relaxed algorithm generates BBR values at most $85,7\%$ higher than those given by the optimal solution. For the USA topology, the time reduction is at most 30% and the BBR differences are at most 70%.

VI. Conclusion

This paper proposed an optimization model to leverage multipath routing and traffic grooming in optical networks with holding time awareness. We show that optical networks can benefit from the proposed model with a lower bandwidth blocking ratio and a better load balancing. We also investigated the impact of HTBalancing on multipath routing based traffic grooming and evaluated the benefit from applying balancing policy. Numerical results showed that the proposed algorithm can decrease the bandwidth blocking ratio of the requests, especially with high network load. All the optimal solutions from the proposed optimization model can fulfill the differential delay constraint which is critical when multipath routing is deployed.

Acknowledgments

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