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Multipath routing with topology aggregation for scalable inter-domain service provisioning in optical networks

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ABSTRACT

In this paper, we propose to use static virtual topology for a scalable inter-domain optical service provisioning, while addressing the resource efficiency issue by using multipath routing. To this end, we discuss methods for virtual topology aggregation with consideration of inter-domain routing, and propose two heuristic algorithms for two representative applications, referred to as real-time streaming and bulk data transfer. We consider specific requirements of each application, including transmission deadline and jitter, and evaluate the impact of differential delay issue of multipath routing on the performance of proposed algorithms. Numerical results show that the proposed multipath routing algorithms yield a low blocking ratio of inter-domain connections even on the static virtual topology, which is known for poor blocking performance otherwise. The resulting differential delay is sufficiently small for the studied applications, and can be compensated with relatively small buffers. We show that a scalable inter-domain service provisioning in optical networks can be achieved by using a combination of static virtual topology and multipath routing.

1. Introduction

In recent years, carriers have witnessed an ever-growing bandwidth demand, driven by the emerging high performance applications in e-science, cloud computing, high-definition visualization, and many more. The global nature of such applications created a pressing need for service provisioning across multiple heterogeneous domains. While optical networks have emerged as the best candidate in serving data-intensive applications, practical approaches to provisioning optical services in multi-domain settings remain a challenge. The demarcation of the domains, either administratively or technically, limits the visibility to the domains to obtain a detailed view of the whole network, challenging the applicability of single-domain Routing and Wavelength Assignment (RWA) algorithms in multi-domain scenarios. Scalability is another issue in inter-domain service provisioning, due to the amount of domain–internal information that needs to be exchanged and updated among domains participating in the end-to-end provision.

To address these challenges, topology aggregation techniques have been proposed, which abstract domain–internal information and advertise information to other domains in a limited, and therefore more scalable fashion. For example, OIF proposed three topologies to be adopted in topology aggregation: *Abstract Node, Abstract Link* and *Pseudo-node*, which represent *Single Node, Full mesh* and *Symmetric Star*, respectively. To guarantee the resource availability to inter-domain connections, the virtual topologies can be created based on transit tunnels that are set up in advance between border nodes of a domain,

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which is referred to as a *static virtual topology* in this paper. The tunnels are typically over-provisioned in order to avoid high blocking ratio of inter-domain traffic. The static virtual topology with over-provisioned transit tunnels, while scalable and effective for inter-domain scenarios, is not resource efficient and often results in excess capacity reserved for inter-domain traffic.

In this paper, we propose a trade-off solution, which utilizes the transit tunnels in each domain to create a static virtual topology for scalability, while overcoming the need to over-provision the tunnels with multipath routing. We propose that each domain computes paths between each pair of border nodes as transit tunnels for inter-domain traffic. Instead of over-provisioning the tunnel created, we propose to use multipath routing to aggregate bandwidth when the tunnels are not sufficient for the dynamic connection demand using single path routing. The aggregated domain information is exchanged between domains only once, based on which a domain chain (path) is computed upon connection request. In this way, we limit the overall amount of information exchanged, and decrease the frequency of the exchange. The end-to-end path computation can be then facilitated by either a Routing Area Leader (RAL), proposed by ITU-T [1], or the Path Computation Element (PCE) proposed in IETF [2].

To study the value of the proposed approach, we present two heuristic algorithms for two representative applications, referred to as real-time streaming and bulk data transfer. In contrast to our previous studies on optimal solutions, which was limited to small networks, heuristics carry potential for practical deployment, on realistic-size networks. Here, we study application-specific requirements, such as transmission deadline and jitter. We consider the differential delay issue of multipath routing and investigate the effectiveness of multipath routing in addressing resource inefficiency of the static virtual topology. We also investigate the performance of multipath routing regarding load balancing by defining the maximum utilization of the available bandwidth on the static virtual topology. Numerical results show that optical networks can yield scalability by the usage of static virtual topology in inter-domain service provisioning, while resolving the resource inefficiency through multipath routing. The proposed heuristic algorithms for both applications can achieve low blocking ratio despite of the static virtual topology, while the resulting differential delay is sufficiently small, and thus can be compensated with small buffers. We also show that splitting traffic on multiple paths for load balancing does not necessary lead to performance improvement regarding the blocking ratio when static virtual topology is used.

The rest of the paper is organized as follows: Section 2 presents the related work and our contribution. Section 3 describes the proposed inter-domain provisioning framework which includes topology aggregation for inter-domain multipath routing and a discussion on the differential delay issue of multipath routing. This section also includes the proposed algorithms for two applications, i.e., bulk data transfer and real-time streaming. Section 4 evaluates the performance of the proposed inter-domain multipath routing on the static virtual topology. Finally, Section 5 draws conclusions.

2. Related work and our contribution

Various methods have been presented for multi-domain optical service provisioning using topology aggregation, with primary focus on lightpath provisioning. For example, a stochastic model is presented in [3] to estimate the effective number of available wavelengths along inter-domain paths, based on which an RWA strategy can successfully set up an end-to-end connection. The ASON hierarchical routing model was discussed by ITU-T and OIF which presented a comprehensive hierarchy to multi-level routing [4,5]. The domains are abstracted by means of virtual topologies which are then used to compute the end-to-end path [1,5]. Here, the interface between the domains, referred to as External Network to Network Interface (E-NNI) was defined to facilitate the information exchange between domains.

Static virtual topology has been proposed to ensure the availability of network resource before traffic arrives, eliminating the need of dynamic set up and tear down of lightpaths. As a consequence, the information exchanged between domains is reduced to the bandwidth availability on the transit tunnels, which significantly reduces the amount of inter-domain information exchange since the domain–internal resource information does not need to be exchanged [6]. However, to ensure a low blocking probability of inter-domain requests, transit tunnels are usually over-provisioned, which in such scenarios with static virtual topology typically results in a poor resource utilization. In this paper, we propose a novel approach to use multipath routing to counter this issue, which, instead of over-provisioning of transit tunnels, can aggregate bandwidth from multiple paths.

However, multipath routing carries a challenge of the differential delay, which is caused by the diversity of paths used between a source and destination pair. The differential delay can affect the quality of services, especially for the real-time applications which have strict requirements of the jitter and delay. Research efforts have been focused on solving the differential delay issue for multipath routing, with primary focus on single domain scenarios. Ahuja et al. [7] studied the problem of minimizing the differential delay in the context of Ethernet over SONET; proposed algorithms select a path for a *Virtually Concatenated Group* (VCG) which has the minimum differential delay [7]. Chen et al. [8] proposed to use multipath routing in the inter-domain service provisioning in circuit switching networks. In [8], the multipath routing solution was derived on the aggregated multi-domain virtual topology, which was formulated as an Integer Linear Programing (ILP) model, where the optimal solutions were tailored to satisfy the connection demands with extremely high bandwidth requirements. The complexity issue of the ILP has been observed in [8], therefore the heuristics targeting different applications are necessary. As a follow-up of this work, we here investigate only the heuristics on inter-domain multipath routing in optical networks, which have a greater potential for practical applicability.

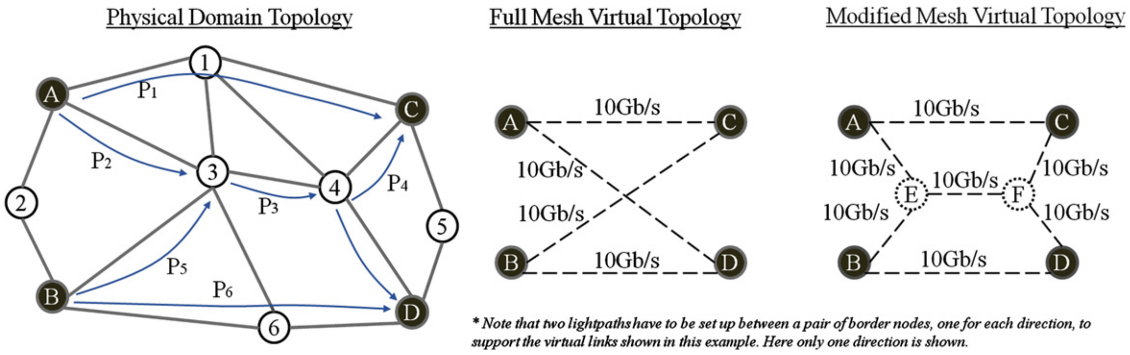

Fig. 1. Illustrative topology aggregation for inter-domain service provisioning in optical networks with and without consideration of multipath routing; here border nodes are marked in black.

3. Inter-domain service provisioning with multipath routing

3.1. Topology aggregation considering multipath routing

Topology aggregation in optical networks can either be implemented by the Routing Area Leader (RAL) [1] or by a Path Computation Element (PCE) deployed in the domains [2]. To create a static virtual topology, a domain sets up lightpaths in advance based on the domain–internal policies and advertises the capacity of virtual links. Fig. 1 shows an example, where the capacity of a wavelength is assumed to be 10 Gbps. To aggregate a static virtual topology with 10 Gbps per virtual link, the optical network can set up lightpaths as shown in Fig. 1, which only reserves 10 Gbps on the link $\langle 3, 4\rangle$. This scheme can avoid redundant resource reservation on the shared physical links, which is resource efficient and effective in inter-domain single path routing. When multipath routing is applied, it may happen that virtual links $\langle A, D\rangle$ and $\langle B, C\rangle$ are taken simultaneously to serve a connection with a bandwidth requirement of 20 Gbps. The service provisioning fails due to the bandwidth overbooking on physical link $\langle 3, 4\rangle$. This can be simply addressed by setting up separate single hop lightpath to support each virtual link, i.e., establish two lightpaths on link $\langle 3, 4\rangle$, however, it is not resource efficient due to the fact that most inter-domain connection demands can be served by single path routing. We present a modified static virtual topology to facilitate inter-domain multipath routing which introduces virtual nodes for the shared segments, as illustrated in Fig. 1. Note that a virtual link here is supported by two lightpaths, one for each direction. The example shown in Fig. 1 only shows lightpaths for the static virtual topology with A or B as ingress nodes.

3.2. Differential delay issue of multipath routing

Service provisioning with multipath routing is constrained by the available buffer size, which should be large enough to compensate for the differential delay issue. When multiple paths are used for a single connection, the diversity of the paths can lead to the flows from different paths arrive at the destination node at different time. Assume the delay of a path P is denoted as d_P, the differential delay of path P_i and P_j is shown in Eq. (1). When K paths are used for a connection between s and d and the traffic routed on path P_i is represented as t_{P_i}, the buffer required to avoid disordering of packets at the destination node, referred to as M_r, is a sum of buffer required to cache flows on all paths except the one with the highest delay. Assume $\tilde{P}$ has the highest delay among all the K paths, M_r is calculated in Eq. (2) [7].

$$dd(P_i, P_j) = |d_{P_i} - d_{P_j}| \tag{1}$$

$$M_r = \sum_{P_i, i=1,2,\ldots,K} t_{P_i} \cdot (d_{\tilde{P}} - d_{P_i}). \tag{2}$$

3.3. Multipath routing algorithms

In inter-domain service provisioning with topology aggregation, a domain chain (path) is first decided based on the aggregated information exchanged between domains, while the inter-domain multipath routing algorithms are applied on the concatenated static virtual topologies of all the domains along the domain chain. The concatenated multi-domain virtual topology is denoted as $G(V, E)$, where V is the set of virtual nodes and E is the set of virtual links and inter-domain links. We propose heuristic algorithms for two representative applications that commonly require multi-domain optical reach, referred to as bulk data transfer and real-time streaming, respectively. In order to explore whether inter-domain service provisioning in optical networks can benefit from multipath routing with regard to load balancing, we define a parameter β which specifies the maximum bandwidth that can be allocated to the incoming connection demand. Assume that the connection demand requiring a bandwidth of B, a path with available bandwidth f_P cannot be used for the connection when $f_P \cdot \beta < B$ even if $f_P \geq B$. For example, if $f_P = 10$ Gbps, the available bandwidth on P that can be allocated to connection demands is constrained to be 9 Gbpbs with $\beta = 0.9$.

3.3.1. Bulk data transfer

The bulk data transfer is a common application in scientific computing, in which the data processed in one site needs to be transferred to another site for further processing. For instance, the CyberShake research requires hundreds of terabytes of data to be transferred between the research centers and TeraGrid center for earthquake forecast research [9]. The destination site is equipped with storage and the data processing starts when all the data arrives. Therefore, a bulk data transfer application does not require to compensate differential delay at the egress node of the destination domain. Such an application requires all data to be transferred within a fixed time frame, i.e., it has a transmission deadline, which is denoted as D_R. It should be noted that the end-to-end delay of bulk data transfer consists of two parts, referred to as path delay and processing delay at the source domain. Assume the size of the data chunk is C and the total bandwidth allocated to the connection is B, the time to send out all data at the source node is calculated as C/B. To serve such applications, the end-to-end delay should not exceed the transmission deadline, i.e., $C/B + D_{\tilde{P}} \le D_R$, where $D_{\tilde{P}}$ is the delay of the longest path used in the connection. A connection demand for the bulk data application is denoted as $R(s, d, C, D_R)$, where (s, d) are the source and destination, respectively. The proposed algorithm for bulk data transfer is shown in Alg. 1.

Algorithm 1: Multipath routing algorithm for bulk data transfer

Input: Virtual topology $G(V, E, \beta)$; Connection request $R(s, d, C, D_R)$
Output: Multipath solution for R
Step 1: *Preprocessing*
Calculate K paths using K-shortest path algorithm [10] and sort the paths in a decreasing order of available bandwidth, $\mathcal{P} = \{P_i\}, i = 1, \ldots, K$, $f_{P_i} > f_{P_{i+1}}$; $\tilde{P}$ is the path with the largest delay in $\mathcal{P}$
Step 2: *Path selection and bandwidth allocation*
$Resv = 0$
for $i = 1, \ldots, K, P_i \in \mathcal{P}$ **do**
    $Resv = Resv + f_{P_i} \cdot \beta$;
    if $(Resv \ge C/(D_R - D_{\tilde{P}}))$ **then**
        break
    end
    Update bandwidth availability in $\mathcal{P}$
    Sort the $\mathcal{P}$ in a decreasing order of available bandwidth
end
Output the selected paths in the solution set $\mathcal{P}'$

The algorithm first calculates a candidate path set, referred to as $\mathcal{P}$, using K-shortest path algorithm [10]. The paths in $\mathcal{P}$ are sorted in a decreasing order of available bandwidth (denoted as f_P). The longest path in $\mathcal{P}$, denoted as $\tilde{P}$, is used as a baseline of the path delay that contributes to the end-to-end delay. The algorithm starts from the widest path and aggregates the available bandwidth from the paths in $\mathcal{P}$. The current bandwidth allocated to R is denoted as *Resv* and the current end-to-end delay is calculate as $C/Resv + D_{\tilde{P}}$, which is compared with the transmission deadline D_R. The algorithm stops when $CResv + D_{\tilde{P}} \le D_R$. Note that the amount of bandwidth from P_i that contributes to *Resv* is constrained by the parameter β, i.e., $f_{P_i} \cdot \beta$. The final value of *Resv* is the actual bandwidth that is allocated to R, which equals B. Assume there are N nodes in the aggregated virtual topology with M links, the worst case complexity for a loopless K-shortest path is calculated in at most $\mathcal{O}(KN(M + N \log N))$ steps [10]. The path selection algorithm considers all the K paths, therefore the complexity of the proposed algorithm is $\mathcal{O}(KN(M + N \log N) + K)$.

3.3.2. Real-time streaming

Real-time streaming is an increasingly important application in scientific computing, telemedicine, remote visualization and video conferencing. In order to prevent video distortion, data is extracted and decoded within a deadline at the receiver [11], which is also referred to as jitter constraint in video streaming. A packet will only stay in the resequencing buffer for at most D_l (decoding deadline), we thereafter use D_l as the maximum differential delay constraint, while considering the available buffer size in the final egress border node as a constraint in the path computation. The connection demand for a real-time streaming application is denoted as $R(s, d, B_R, D_l)$, where (s, d) are source and destination respectively and B_R is the required bandwidth. The proposed multipath routing algorithm for real-time streaming is shown in Alg. 2.

The algorithm first tries to find a single path solution for the request R by checking the widest path between s and d, while the parameter β is applied to constrain the maximum available bandwidth that the connection can be allocated. If the connection request cannot be served with the widest path, the algorithm moves to find a multipath solution. K-shortest paths are computed [10] and ordered in $\mathcal{P}$ with a decreasing order of available bandwidth before further processing. The path selection and traffic splitting strategy is developed around a guess of the path chosen from $\mathcal{P}$ as the longest path, denoted as $\tilde{P}$, and then composing a corresponding candidate path set, i.e., $\mathcal{P}'$, by choosing all the paths with a delay no larger than $\tilde{P}$. The mapping starts from choosing the widest path as the first guess and stops when the solution is found. For instance, assume path P_i is chosen to be $\tilde{P}$, the algorithm will compare the paths in $\mathcal{P}$ with P_i and put all the paths with delay that is not larger than D_{P_i} in the candidate path set $\mathcal{P}'$. For instance, if four paths are calculated and ordered in $\mathcal{P} = \{P_1, P_2, P_3, P_4\}$, with the delay of each path as $D_{P_1} = 4, D_{P_2} = 2, D_{P_3} = 3$, and $D_{P_4} = 5$. When P_1 is chosen as the first guess to be $\tilde{P}$, the current candidate path set $\mathcal{P}'$ is composed as $\mathcal{P}' = \{P_1, P_3, P_2\}$. In each inner loop, the algorithm tries to find a solution from $\mathcal{P}'$. The differential delay constraint is first checked and is followed by the check of the bandwidth requirement. The current bandwidth allocated to R is *Resv*, which is constrained by β, i.e., $Resv = Resv + f_{P_k} \cdot \beta$, where P_k is the path that is being checked. The traffic is split into the selected paths proportionally and the buffer size constraint is checked at the end. If all paths can be reserved simultaneously and the required buffer M_r is not larger than the available buffer size at the destination, denoted as M_d, the algorithm stops and it returns the magnitude of the sub-flows. Otherwise, it goes to the outer loop and starts with another $\mathcal{P}'$. The algorithm stops only when a solution is found or all paths in $\mathcal{P}$ are exhausted. When the former happens the algorithm will output the flows while the latter case will reject the connection request.

Algorithm 2: Multipath routing algorithm for real-time streaming

Input: Virtual topology $G(V, E, \beta)$; Connection request $R(s, d, B_R, D_l)$
Output: Multipath solution for R
//Serve the connection demand with single path routing first; otherwise use multipath routing.
Find the widest path P_0 between s and d;
if $f_{P_0} \cdot \beta \geq B_R$ **then**
  Output P_0 as the solution and break;
end
else
  Calculate K paths by K-shortest path algorithm and sort in the decreasing order of the available bandwidth, $\mathcal{P} = \{P_i\}, i = 1, \ldots, K, f_{P_i} > f_{P_{i+1}}$; $\tilde{P}$ is the path with the largest delay in $\mathcal{P}$.
end
//Path selection and bandwidth reservation.
for $i = 1, \ldots, K, P_i \in \mathcal{P}$ **do**
  $\mathcal{P}' = \emptyset$; $\tilde{P} = P_i$;
  for $P_j \in \mathcal{P}$ **do**
    if $D_{P_j} \leq D_{\tilde{P}}$ **then**
      $P_j \to \mathcal{P}'$;
    end
  end
  for $P_k \in \mathcal{P}'$ **do**
    if $D_{\tilde{P}} - D_{P_k} \leq D_l$ **then**
      $Resv = Resv + f_{P_k} \cdot \beta$;
      if $Resv \geq B_R$ **then**
        break;
      end
    end
  end
  // Output the selected paths as the candidate solution.
  for *each path P_k in the selected paths* **do**
    // proportional bandwidth reservation on the selected paths;
    $t_{P_k} = B_R \cdot \frac{f_{P_k}}{Rev}$;
  end
  // compare the buffer size constraint;
  if $\sum_{P_k} t_{P_k} \cdot (D_{\tilde{P}} - D_{P_k}) \leq M_d$ **then**
    Output solution and break;
  end
end

Path selection and traffic splitting have time complexity of $\mathcal{O}(K^3)$. The complexity to find the widest path in the first step is the same as the weighted Dijkstra shortest path, i.e., $\mathcal{O}(M + N \log N)$; and the worst case time complexity of the loopless K-shortest path is $\mathcal{O}(KN(M + N \log N))$ [10], where N and M represent the number of nodes and links in the virtual topology respectively. Therefore, the proposed algorithm for inter-domain streaming has a time complexity of $\mathcal{O}(KN(M + N \log N) + K^3)$.

4. Performance evaluation

In this section, we evaluate the proposed heuristic algorithms on a multi-domain network composed of three concatenated domains, each with a NSFnet topology, as shown in Fig. 2. In each domain, the virtual topology is composed of the lightpaths computed in advance between the border nodes, which are marked with dotted lines. We assume that the domain chain (path) has been computed and aim to evaluate the performance of the proposed multipath routing algorithms for bulk data transfer and real-time streaming applications. The studied multi-domain optical network has only three domains, which includes all the critical elements of inter-domain service provisioning, i.e., source domain (Domain 1), destination domain (Domain 3) and transit domain (Domain 2). It is therefore generic enough to evaluate the proposed algorithms. In Fig. 2, links connecting two domains are marked with bold lines. The total capacity of the lightpaths set up on the inter-domain links is 40 Gbps and the capacity of the virtual links of Domain 1 and Domain 3 are assumed to be 10 Gbps. Given the fact that domain 2 is subject to higher load than the other domains, the capacity of the virtual links of Domain 2 is set to be 40 Gbps. The buffer size of all border nodes are assumed to be the same, i.e., 10 MB. For both bulk data transfer and real-time streaming applications, 10^5 connection requests arrive in a Poisson process and are uniformly distributed among all source and destination pairs.

Bulk data transfer is featured by the transitory connection time of each chunk, hence the proposed algorithm is evaluated against the arrival rate which is defined as the average number of connection requests arrival per second. The size of the data chunk to be transferred on each connection is assumed to be 10 GB. The blocking ratio is used as the performance index, which is defined as the percentage of rejected requests in all connection requests. As for the real-time streaming application, *network load A* (in Erlang) is used for performance evaluation, which is defined as $u * h$, where u is connection arrival rate and h is the mean connection holding time. The bandwidth required by the connection demands for the real-time streaming application varies from 250 Mbps to 8 Gbps and the number of connections is inversely proportional distribution of required bandwidth, i.e., the bandwidth requirement distribution of 250 Mbps : 500 Mbps : 1 Gbps : 2 Gbps : 4 Gbps : 8 Gbps leads to a proportion of the number of connection demands as 32 : 16 : 8 : 4 : 2 : 1. *Bandwidth Blocking Ratio(BBR)* is used to evaluate the proposed algorithm related to the real-time application, which is defined as the sum of bandwidth requested by the blocked connections divided by the total bandwidth requests.

In the results that follow, we first evaluate the necessity of allowing multipath routing to achieve a trade-off between scalability and resource efficiency by comparing with single path routing. We show the effectiveness of multipath routing on targeting the resource efficiency issue of the static virtual topology in inter-domain service provisioning. The performance evaluation is focused on the blocking and link utilization. We also analyze the average differential delay and the required buffer size of the proposed algorithms.

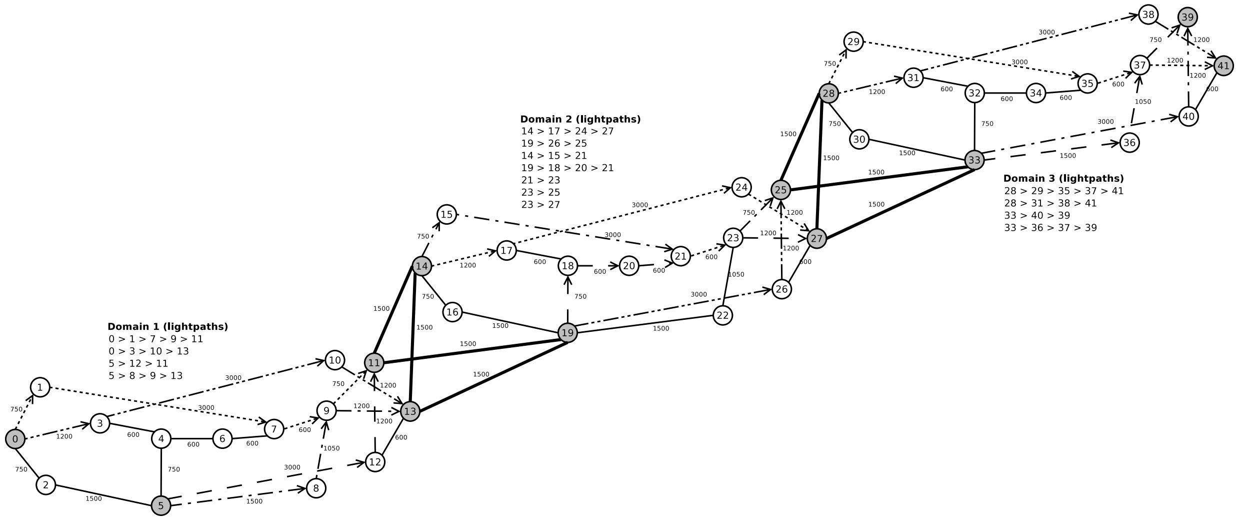

Fig. 2. The three-domain topology used in performance evaluation.

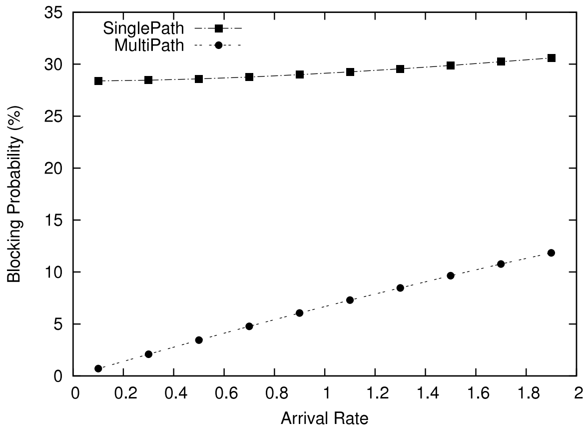

Fig. 3. Blocking ratio of connections for bulk data transfer with $\beta = 1$.

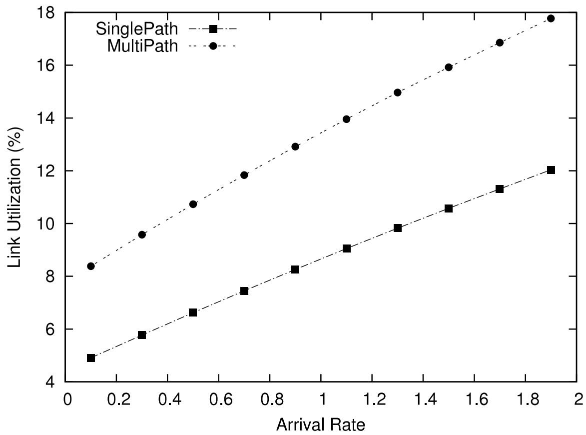

Fig. 4. Link utilization of bulk data transfer applications with $\beta = 1$.

4.1. Bulk data transfer

We first study the drawback of using a static virtual topology for inter-domain service provisioning by showing the performance of single path routing. As shown in Fig. 3, using static virtual topology leads to a high blocking ratio with single path routing. Around 27% connection demands from bulk data transfer application are blocked, especially more than 30% blocking is observed when the average arrival rate is two per second. It is caused by the static virtual topology without over-provisioning, on which the single path routing may also lead to severe load imbalance. Fig. 3 shows that the proposed multipath routing algorithm can significantly reduce the blocking ratio. Less than 15% blocking happens even when the arrival rate is two per second. The high acceptance does not lead to the significant increase of the average link utilization, as shown in Fig. 4. Only 6% increase of the average link utilization has been observed when the arrival rate is two while the blocking ratio has been reduced around 20%.

Multipath routing is known with its capability of load balancing. We therefore investigate its capability of load balancing in optical networks with different value of β. As shown in Fig. 5, the decrease of the β leads to a reduction of the link utilization thanks to the load balancing. Despite

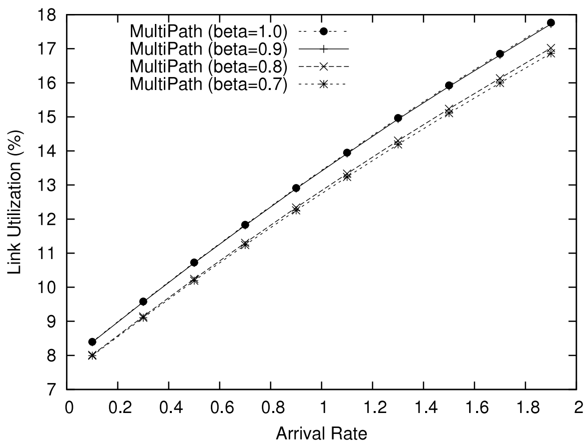

Fig. 5. Link utilization of bulk data transfer with different β.

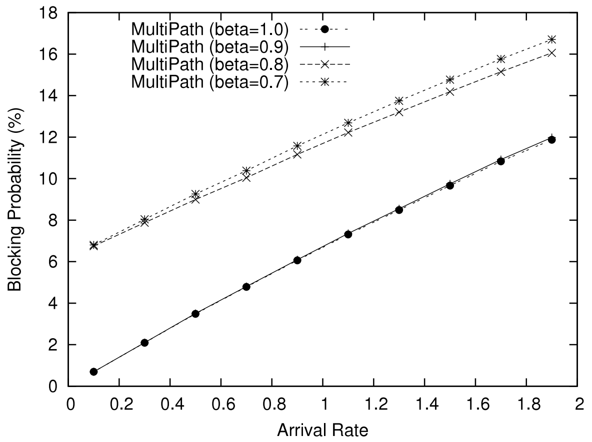

Fig. 6. Blocking ratio of bulk data transfer applications with different β.

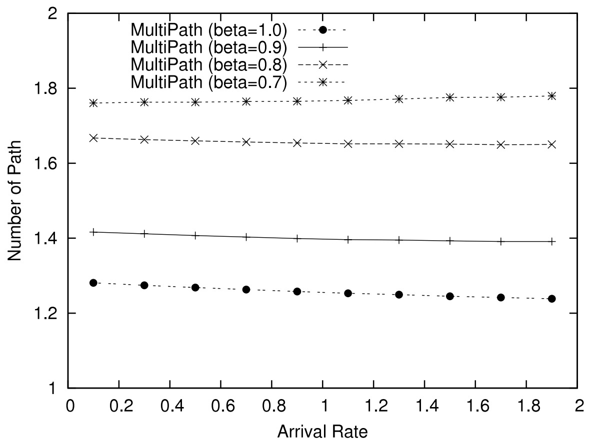

Fig. 7. The average number of paths taken in the connections for bulk data transfer applications with different β.

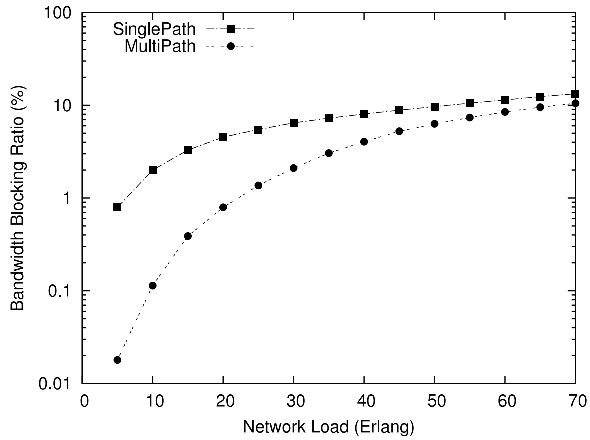

Fig. 8. Bandwidth Blocking Ratio of the inter-domain real-time streaming with $\beta = 1$.

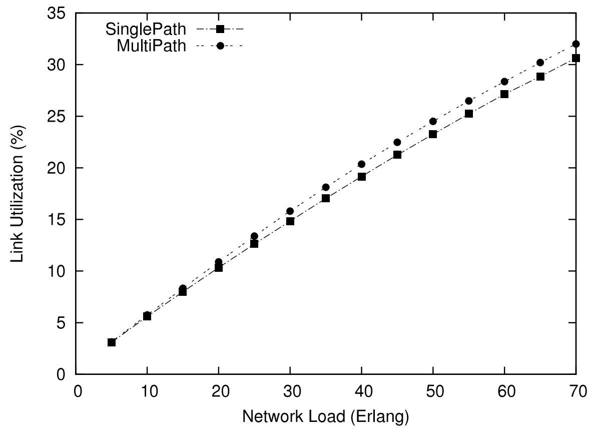

Fig. 9. Link utilization of the inter-domain real-time streaming with $\beta = 1$.

the small difference between $\beta = 1, 0.9$ and $\beta = 0.8, 0.7$, up to 1% decrease of the average link utilization is observed between $\beta = 0.9$ and $\beta = 0.8$ at *Arrival Rate* $= 2$. Here, the arrival rate is defined as the number of connection demands per second. However, it causes around 6% increase of blocking probability as shown in Fig. 6. It shows that the decrease of β value causes the reduction of the actual available bandwidth to the connection request, which increases the chance to use multipath routing. As a conclusion, using multipath routing does not necessary lead to the performance improvement in case of the bulk data transfer where the connection duration is usually short. Finally, we studied the average number of paths that are used in the connections for bulk data transfer application. It can be seen in Fig. 7, our algorithm takes two paths in average per connection despite of the limit resource on the static virtual topology.

4.2. Real-time streaming

Inter-domain service provisioning for a real-time streaming application with multipath routing is challenging due to the differential delay issue. In the results that follow, we not only show the benefits of using multipath routing, but also the cost of the multipath routing solutions which is reflected by average buffer size and average differential delay. As shown in Fig. 8, multipath routing can decrease the bandwidth blocking ratio. At first glance, these are intuitive results. However, a very slight increase in average link utilization can be observed in Fig. 9 (y axis in logscale), especially when network load is high. For instance, average link utilization increases at most 2% at network load of 70 Erlang. It implies that the proposed algorithm is capable of balancing the traffic when the network is heavily loaded.

We further study the impact of the parameter β. As shown in Fig. 10, a strict constraint on the available bandwidth can lead to a significant increase in the bandwidth blocking ratio. 10% bandwidth blocking ratio is observed for $\beta = 0.7$ even when the network load is lower than 20 Erlang. Inappropriate values of β can diminish the advantages of multipath routing. However, a carefully chosen β can achieve comparable bandwidth blocking ratio values while balancing the traffic, for instance, a trade-off solution is obtained with $\beta = 0.9$ in this case study shown in Fig. 11.

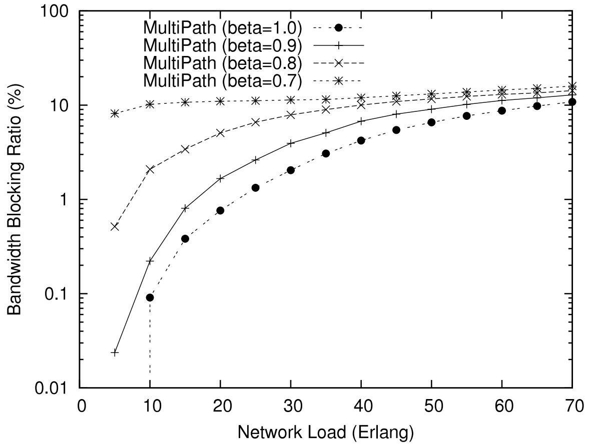

Fig. 10. Bandwidth Blocking Ratio of the inter-domain real-time streaming with different β.

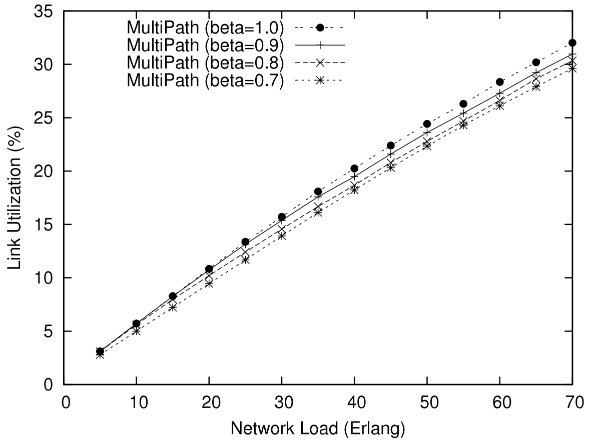

Fig. 11. Link utilization of the inter-domain real-time streaming with different β.

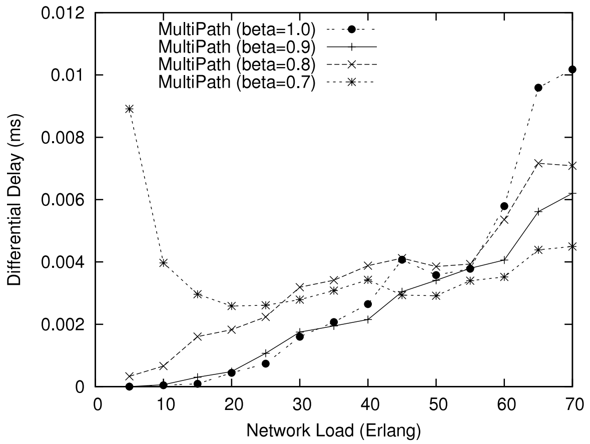

Fig. 12. The average differential delay in the connections for inter-domain real-time streaming with various β.

Finally, we study the cost of multipath routing by showing the average differential delay and buffer size. It should be noted that all the solutions found by our algorithm

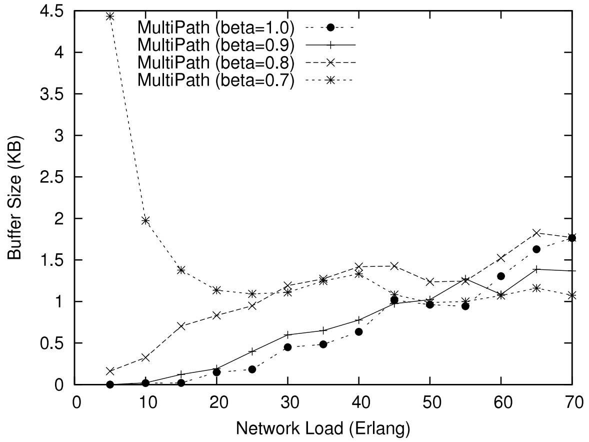

Fig. 13. The average buffer size required by the connections for inter-domain real-time streaming with various β.

respect the available buffer size constraint, while the results shown in the following aims to quantitatively illustrate the cost of the multipath solutions in inter-domain provisioning. Fig. 12 shows the the average differential delay of using multipath routing with different values of β. It can be seen that the small values of β lead to more frequent traffic splitting, which results in the large average differential delay. As a result, the buffer size requirements are also increased as shown in Fig. 13. However, the average differential delay of multipath solutions are small, generally less than 0.008 ms when network load is below 70 Erlang. The average buffer size required by the solutions of the proposed algorithm is generally less than 1.5 kB, which is also comparably low. In summary, our algorithm is able to find multipath solutions for the inter-domain streaming applications while requiring comparably small buffer size. In addition, the relatively low bandwidth blocking ratio, which is less than 1% when $A \leq 30$ Erlang and it is at most 1% under $A = 70$ Erlang, implies that our framework can achieve good performance and yet maintain scalability.

5. Conclusions

In this paper, we presented an inter-domain provisioning scheme for optical networks which utilizing static virtual topologies in combination of multipath routing. We proposed to use static virtual topology to achieve scalability, while using multipath routing to overcome resource inefficiency of static topologies. We presented a virtual topology aggregation method with consideration of inter-domain multipath routing and proposed two heuristic algorithms for two representative applications, referred to as bulk data transfer and real-time streaming, respectively. The numerical results showed that the proposed multipath routing algorithms can decrease the average blocking ratio and increase average link utilization for both applications on the static virtual topologies without over-provisioning. For the real-time streaming application, we considered the available buffer size as a critical constraint in the path computation and showed that our algorithm can find solutions with sufficiently low average differential delay and buffer size requirement. We showed that frequently using multipath routing for load balancing does not necessarily contribute to performance improvement regarding the blocking ratio. However, we have shown that a carefully selected β, that specifies the maximum usable bandwidth on the static virtual topology can achieve a performance trade-off with regard to the load balancing and bandwidth blocking ratio. In conclusion, a scalable inter-domain service provisioning in optical networks can be achieved by using a combination of static virtual topology and multipath routing. The presented scheme is expected to be compatible and easy to implement in the current standards, such as Path Computation Elements (PCEs), with tunnel creation in the carrier Ethernet standards, PBB-TE and MPLS-TP, which is the subject of our future work.

References

[1] G. Bernstein, B. Rajagopalan, D. Saha, Optical Network Control-Architecture, Protocols and Standards.

[2] IETF, A backward recursive PCE-based computation (BRPC) procedure to compute shortest constrained inter-domain traffic engineering label switched paths.

[3] M. Yannuzzi, X. Masip-Bruin, S. Sanchez-Lopez, E. Tordera, J. Sole-Pareta, J. Domingo-Pascual, Interdomain RWA based on stochastic estimation methods and adaptive filtering for optical networks, in: IEEE Globecom 2006.

[4] ITU-T recommendation G.7715/Y.1706 (2002), architecture and requirements for routing in the automatically switched optical network.

[5] S. Sanchez-Lopez, X. Masip-Bruin, E. Marin-Tordera, J. Sole-Pareta, J. Domingo-Pascual, A hierarchical routing approach for GMPLS based control plane for ASON, in: Proc. of IEEE ICC, 2005, pp. 1683–1687.

[6] M. Chamania, A. Jukan, A survey of inter-domain peering and provisioning solutions for the next generation optical networks, IEEE Communications Surveys and Tutorials 11 (1) (2009) 33–51.

[7] S. Ahuja, T. Korkmaz, M. Krunz, Minimizing the differential delay for virtually concatenated Ethernet over SONET systems, in: Proc. ICCCN, 2004, pp. 205–210.

[8] X. Chen, M. Chamania, A. Jukan, A. Drummond, N.L.S. Fonseca, On the benefits of multipath routing for distributed data-intensive applications with high bandwidth requirements and multidomain reach, in: Proc. IEEE CNSR, Canada, May, 2009.

[9] TeraGrid. https://www.teragrid.org/.

[10] J.Y. Yen, Finding the K shortest loopless paths in a network, Management Science 17 (11) (1971) 712–716.

[11] S. Mao, S.S. Panwar, Y.T. Hou, On minimizing end-to-end delay with optimal traffic partitioning, IEEE Transactions on Vehicular Technology 55 (2) (2006) 681–690.