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A Novel Priority-Based Path Computation Approach for Finding Domain Sequences in PCE-Based Multi-domain Networks

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ABSTRACT

During recent decades new routing paradigms based on policies and quality of service provisioning have been proposed. The aim of these constraint-based path selection algorithms is to satisfy a set of quality of service constraints. This can help to reduce costs and balance network load. Path computation algorithms pose new challenges when extending them to larger inter-domain networks. The process of path computation in these complex cases could be delivered to the external nodes like PCEs. In inter-domain cases, path computation schemes are more prone to blocking due to the long response time of the requests. To address this issue, we propose an algorithm to find the domain sequences in computing the end-to-end path from the source to the destination. The proposed algorithm also increases the number of successful requests while minimizing the blockage in network. The main advantage of the algorithm is to improve the overall network utilization, which can be seen in simulation results.

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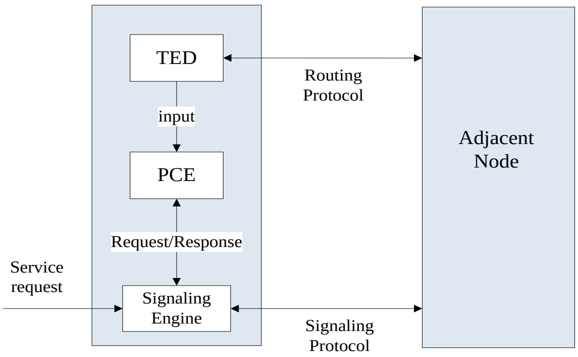
1. INTRODUCTION

With the rapid growth of current transport network infrastructures, the requirement for effective traffic engineering to efficiently manage network resources is rapidly expanding from single-domain to multi-domain networks. In multi-domain network, routing domains managed by different network providers, have their own routing policies and information [1]. As a result, computing optimal routes across multiple domains presents a huge problem, because no single point of path computation is aware of all of the links and resources in each domain. In particular, network providers require efficient mechanisms to perform path computation between source and destination nodes belonging to different administrative domains [2]. However, in these cases one entity cannot have visibility on all the required resources information due to the scalability and privacy issues.

In this context, IETF has proposed path computation element (PCE) architecture [3] to deal with constraint-based path computation challenges in multi-domain network. PCE is a special entity which can be located at a network element or can be as an independent entity and receives path computation requests from Path Computation Clients (PCCs). PCE computes optimal paths using its traffic engineering data base (TED) in a single domain, but it has limited routing information from other domains (Fig.1).

Therefore, computing the optimal paths in multi-domain scenarios requires cooperation between multiple PCEs in every traversed domain, each responsible for its own domain [4]. Looking at standardization, two general inter-domain path computation approaches have been proposed for inter-domain path computation using PCE architecture: per-domain path computation [5], and Backward Recursive PCE-based Computation (BRPC) [6]. Both mechanisms assume that the sequence of domains to be crossed between source and destination is known in advance.



Fiqure1: Path Computation Element.

The main contribution of our paper is to propose a novel method to establish the optimum path when the sequence of domains is not known in advance. The rest of this article is organized as follows. Section 2 presents related work on the topic. Section 3 describes multi-domain network model and the functions required in an inter-domain path computation algorithm. In section 4, the proposed method is described in detail. Section 5 includes the simulation results and discusses the obtained results. Section 6 concludes the paper with final remarks.

2. RELATED WORK

There are a lot of ongoing researches on inter-domain path computation schemes. These researches can be divided into two classes from the perspective of routing architecture and protocol [7]. One class focus on extending the functionalities of border gateway protocol (BGP) [8]-[9] and the other is attempting to design novel architecture or solutions beyond BGP.

BGP was introduced to provide reachability information in the whole Internet. In particular, BGP selects domain sequences based on the lowest number of traversed domains. But, mainly due to the lack of QoS routing capabilities and scalability issues, BGP has never achieved a significant consensus within providers and is inadequate for most inter-domain applications.

Aiming to support multi-domain traffic engineering, some researches propose new architectures beyond extending BGP protocol. The most considered architectures are Path Computation Element (PCE) architecture [3] and Automatically Switched Optical Network (ASON) [10]. As discussed previously, two general mechanisms have been proposed with PCE architecture: per-domain and BRPC.

In per-domain path computation method, the path is computed during the signaling process on a per-domain basis. In other words, every intermediate domain independently computes individual path segments. Each of these segments results in a path that crosses the domain to provide connectivity to the next domain in the sequence. The complete path is obtained by joining the computed segments. Per-domain path computation may lead to sub-optimal end-to-end paths. Because selecting a boundary node for next domain may lead to a very poor path across that next domain [11].

In BRPC approach, Path Computation Client (PCC) sends a path computation request to a PCE responsible for the ingress domain. This request forwarded between PCEs, domain by domain, until it reaches to the destination domain. The PCE in destination domain creates a set of optimal paths from all of the domains called a Virtual Shortest Path Tree (VSPT) and send it back to PCE in previous domain. As the VSPT is passed back toward the requesting PCC, each intermediate PCE computes optimal paths in its own domain and adds its local path information to the received VSPT. Then, PCC selects the optimal end-to-end path from the tree. Since the path is computed from egress domain toward ingress domain, this procedure is backward and it is recursive, as the same sequence of operation is repeated for every intermediate domain [12]. In both of these approaches, the sequence of domains to be traversed is determined before the path computation process.

In the case that domain sequences is not known, [5] suggests to use the IP shortest path as advertised by BGP. However, IP forwarding path does not guarantee the presence of sufficient bandwidth. Thus, establishing even a sub-optimal path requires more signaling and crankback routing attempts [13]. Another way to compute optimal end-to-end path without any pre-determined domain sequences, is Path Computation

Flooding (PCF) that is introduced in [14]. In the PCF method, the ingress PCE sends the path computation request to all neighboring domains. Then, the PCE responsible for egress domain computes its local VSPT and send it back to all adjacent domains. Each PCE in turn constructs a VSPT and passes it on to all of its neighboring PCEs until the ingress PCE receives a VSPT from each of its neighboring domains and select the optimum path. Clearly, this mechanism has significant scalability problem and network overhead that lead to discard this approach for large multi-domain networks.

The work presented by [15]-[17], extended PCE architecture to allow the optimum sequence of domains to be selected through the use of a hierarchical relationship between domains. In the hierarchical PCE, a parent PCE maintains a domain topology and interconnections between child domains. There is a centralized global PCE that aggregates information from each domain to calculate the optimal inter-domain path. However, hierarchical PCE model is not applicable to large groups of domains such as Internet [11].

3. MAIN FEATURES OF NETWORK MODEL

In order to present the proposed method, multi-domain network is modeled as a graph $G(V,E)$, where V and E represent the set of nodes and link, respectively. This global graph joins D sub-graphs, $G^i = \{V^i, E^i\}$, where each sub-graph presents one domain and D is the total number of domains. In particular, $V^i = \{v_1^i, \dots, v_{N^i}^i\}$ is the set of intra-domain nodes in G^i, so that N^i is the total number of nodes in that domain and $V^i = \{\forall\, i,j \,|\, i \neq j, i \geq 1, j \leq D, V^i \subset V\} \Rightarrow V^i \cap V^j = \emptyset$, $E^i = \{(u,w) \in E \,|\, v_u^i, v_w^i \in V^i, u \neq w\}$ is the set of intra-domain links and inter-domain links defined as $\rho_{mn}^{ij} = \{(v_m^i, v_n^j) \in E \,|\, v_m^i \in V^i, v_n^j \in Vj; 1 \leq m \leq Ni,\ 1 \leq n \leq Nj; m \neq n,\ i \neq j\}$. Note that each domain Gi may have one centralized PCEi responsible for computing the path inside it or multiple distributed PCEs, PCE_j^i, may collaboratively calculate the optimal path inside the domain.

To find a path from the source assumed in G^1 to the destination assumed in G^D, we use two basic messages that can be incorporated into *PCReq* and *PCRep* messages in the PCEP protocol [18].

- *[Path Request]*
- *[Path Reply]*

In this model, we also use two other messages: *[Path Request-confirm] and* [*Path Reply-confirm]*. The functionality of these messages is similar to RSVP-TE *Path* and *Resv* messages exchanged during the deployment of an LSP.

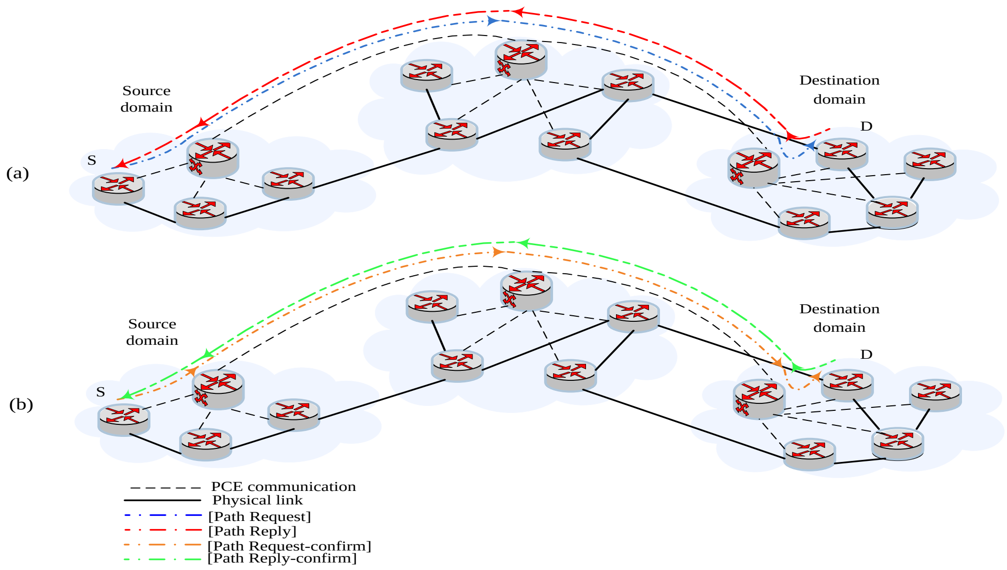


Figure2: The Reservation Mechanism.

These messages are used to confirm recipient of request and reply messages. The service of the source PCE , PCE_1^1, is triggered by the PCC. Then, PCE_1^1 forward the request toward the destination PCE. During route computation, the required resources are compared with the available resources. If the available resources are not sufficient, a *PathErr* Message will be returned. After pruning non-feasible and non-promising paths, one or a set of paths will be returned to the requesting PCC and it can select the best one through the returned paths and signal the deployment of LSP, Fig.2.

4. MULTI-DOMAIN PATH COMPUTATION MECHANISM

As discussed previously, no applicable mechanism has been so far presented for obtaining domain sequence in PCE-based path computation procedures to large groups of domains. So we have to pre-determine the domain sequences in advance or flood the request to find it. Since flooding approaches impose a large overhead in terms of traffic and resource reservation in network, applying them to a large network is not considered feasible or desirable. In this context, some researches propose to use the hierarchical PCE model. But this model is defined to operate within a limited set of domains with known relationships.

Aiming to address this issue, we introduce a mechanism to establish the optimum path when the sequence of domains is not known in advance. As will be shown in the obtained results, this mechanism makes a good trade-off between blocking failures and network control overhead.

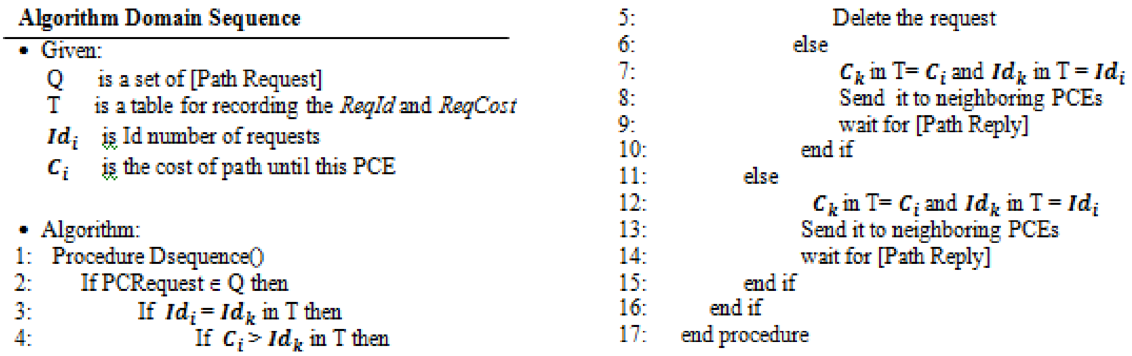
4.1. Domain Sequence Procedure

In this section, we propose a scalable method for finding the domain sequence in multi-domain network. The proposed method is implemented with a simple yet effective mechanism which consists in recording the *ReqId* and *ReqCost* in each PCE. The *ReqID* indicates to the number of request and the *ReqCost* is simply the total cost of the path from source to the current PCE.

As no pre-defined sequence of domains is determined, each PCE which has no visibility on the destination forwards the request to all neighbor PCEs when the request is for a node in another domain. If the request is for a node inside the same domain, it will be forwarded only to intra-domain neighbors. When a request message passes through a PCE, PCE records its *ReqId* and *ReqCost* which is carried in the request messages. This may happen in two states:

- If the *ReqId* is not already registered in that PCE, then the received message is the new one, so *ReqId* and *ReqCost* will be recorded in the table of PCE.
- There is a *ReqId* with the same value of received message's Id in PCE table. In this case, the *ReqCost* values of PCE and request message will be compared with each other. If the value of *ReqCost* recorded in PCE is greater than the *ReqCost* of received message, previous value is replaced with the new one and after that the message will be sent to neighbors. Otherwise, the received request will be deleted, because we have a route with lower cost from source to the current PCE.

After pruning non-feasible and non-promising paths, one or more than one request message with specific *ReqId* is forwarded to the destination domain. The replies to this request consist of computing all possible paths in each domains and adding the results as a Virtual Shortest Path Tree (VSPT) in the reply. Then, they are returned upstream, backward recursively, to PCE_1^1. Fig. 3 illustrates the pseudo-code of the domain sequence procedure.



```
Algorithm Domain Sequence
• Given:
    Q      is a set of [Path Request]
    T      is a table for recording the ReqId and ReqCost
    $Id_i$    is Id number of requests
    $C_i$     is the cost of path until this PCE

• Algorithm:
  Procedure Dsequence()
      If PCRequest ∊ Q then
          If $Id_i = Id_k$ in T then
              If $C_i > Id_k$ in T then
                  Delete the request
              else
                  $C_k$ in T= $C_i$ and $Id_k$ in T = $Id_i$
                  Send  it to neighboring PCEs
                  wait for [Path Reply]
              end if
          else
              $C_k$ in T= $C_i$ and $Id_k$ in T = $Id_i$
              Send it to neighboring PCEs
              wait for [Path Reply]
          end if
      end if
  end procedure
```

Figure3: Domain Sequence algorithm.

4.2. The Impact of QoS Metrics in Domain Sequence

For determining the path cost, we can use one or more metrics in path selection procedure. Aiming to do this, we use a linear combination of different routing metrics according to following equation:

$$C_{PCE}^{i} = \sum_{j=1}^{k} c_{PCE}^{j} + M_i \tag{1}$$

$$M_i = \sum_{\forall k} \alpha_k * Metric_k, \qquad \sum_{\forall k} \alpha_k = 1 \tag{2}$$

Where p is the number of nodes in the path from source to destination, D_q^j is the average queuing delay of PCE j and D_l^j is link delay between PCE j and its neighbors.

Queuing delay is a function of the number of packets in the queue. Packet arrival and packet departure changes queue length and as result changes queuing delay. Thus a node monitors its queuing delay periodically. Due to pay attention to the past history of the node status, D_q^k can be computed by using an Exponential Weighted Moving Average (EWMA). When a data packet arrives, each PCE monitors its current queuing delay (D_{cur}^k) and calculates an average value (D_q^k) using EWMA formula as follows:

$$D_q^k = (1-\omega) \times D_q^k + \omega \times D_{cur}^k \qquad 0 \le \omega \le 1 \tag{4}$$

Where, ω is the moving average coefficient with older values.

In particular, considering both jitter and delay in path selection, makes a good trade-off between path latency and distance. This leads to choose the low-cost paths in network.

We computed the cost of PCE_j (C_j) as follow:

$$C_j = \alpha H_j + (1-\alpha) D_j \tag{5}$$

Where H_j is the number of hops to PCE_j through the source and D_j is the path delay through PCE_j. So, we can rewrite the relation (6) as follow:

$$C_{PCE}^{i} = \sum_{j=1}^{k} C_{PCE}^{j} + \alpha H_{PCE}^{i} + (1-\alpha) D_{PCE}^{i} \tag{6}$$

The algorithm at first eliminates the paths with delay larger than the requested delay. Then, shortest path is selected among the remaining paths. Since we consider path latency and distance in computing the cost, the first request arrived to PCE is the best one and will have the lowest cost.

4.3. Example of Finding Domain Sequence Procedure

The description can be better completed with the help of an example. Fig.4 illustrates a simple example of network topology. When a message is received by *A* which is not intended for it, *A* will send the message for all of its neighbors. As seen, a message can be sent from two different paths: *A→C→D* and *A→B→C→D*. Suppose there is a message with *ReqId= 25*, which is forwarded from *A* to *D*.

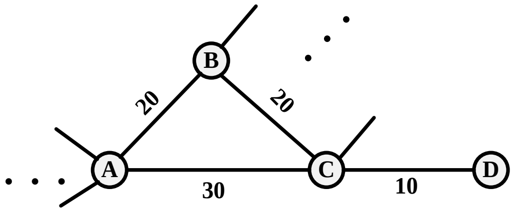


Figure4: The example of domain sequence procedure.

With receiving the first message by C, it records the *ReqId* and *ReqCost* of the request message in its local table. Suppose the first message is received from A. By receiving the second message from B, the *ReqID* of the message will be searched in the local table of C. In this example, the recorded cost is 30 and the cost of the received message from B is 40. So, the received message from B will be deleted because of its higher cost. That's because we previously received and forwarded the same request by lower cost.

4.4. Analysis of the Procedure Message Rate

In our method, each PCE sends the path computation request to all neighboring domains like flooding approaches. Flooding in networks, where connectivity is high, imposes a large overhead. In this method, message complexity in the worst case is $O(ND)$, where N is the number of nodes and D is the average degree of links at a node. Because one node forwards a request message through every outgoing link. Let deg_i be the degree of node i, [19] proves that the number of messages that are generated by each flooding procedure can be obtained by the following equation:

$$deg_1 + \sum_{i=2}^{N}(deg_i - 1) = 1 + \sum_{i=1}^{N}(deg_i - 1) = 1 + \sum_{i=1}^{N} deg_i - N = 1 + ND - N = N(D-1) + 1 \approx O(DN) \tag{7}$$

This is the lower bound of flooding a message. Because in this case we suppose each node receives the message only once. But in particular, one node can receive the messages from its entire links. So, we can calculate the worst case of flooding a message as follow:

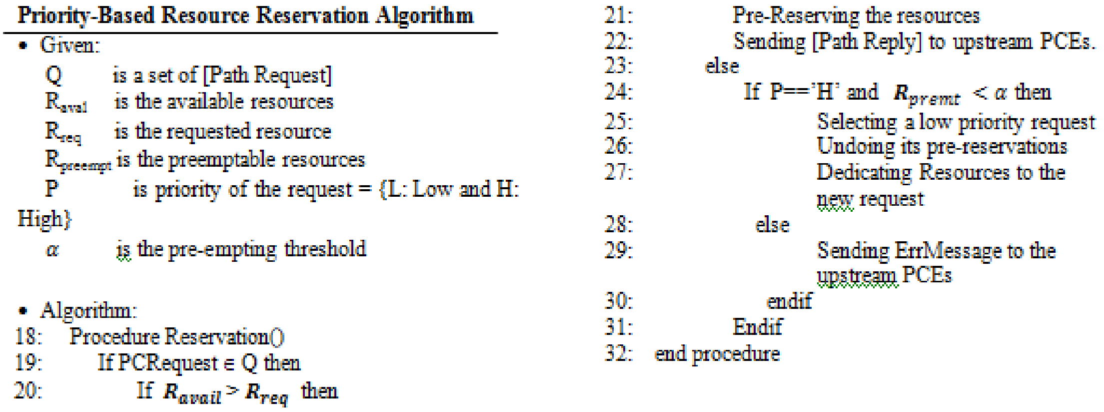
$$D\left[deg_1 + \sum_{i=2}^{N}(deg_i - 1)\right] = D\left[1 + \sum_{i=1}^{N} deg_i - N\right] = D\left[1 + \sum_{i=1}^{N} deg_i - N\right] = D(1 + ND - N) = ND(D-1) + 1 \approx O(D^2N) \tag{8}$$

Pruning the forwarded messages will decrease the number of flooded messages in the whole network. As a result with pruning, the number of generated messages can be equal to the lower bound or close to the lower bound.

4.5. Combining Domain Sequence Computation and Path computation Mechanism

All of inter-domain path computation procedures pose a significant PCE response time that could result in blockage during actual deployment [20]. In inter-domain enviroment, there is a significant time interval from sending a request until receiving a reply for it. This increases the probability of deployment failure in complex inter-domain path computations.

Aiming to address this limitation, [20] proposes a path computation procedure based on the pre-reservation of the resources dedicated to the path. Resource pre-reservation method ensures that path resources from the source PCE to the destination PCE are reserved before the actual deployment of LSP. Pre-reservation technique also allows us to consider the priority of a computation request.



Priority-Based Resource Reservation Algorithm

- Given:
  - Q is a set of [Path Request]
  - R_{avail} is the available resources
  - R_{req} is the requested resource
  - $R_{preempt}$ is the preemptable resources
  - P is priority of the request = {L: Low and H: High}
  - α is the pre-empting threshold
- Algorithm:

```
Procedure Reservation()
    If PCRequest ∈ Q then
        If $R_{avail} > R_{req}$ then
            Pre-Reserving the resources
            Sending [Path Reply] to upstream PCEs.
        else
            If P=='H' and $R_{premt} < \alpha$ then
                Selecting a low priority request
                Undoing its pre-reservations
                Dedicating Resources to the new request
            else
                Sending ErrMessage to the upstream PCEs
            endif
        Endif
end procedure
```

Figure5: Priority-based Pre-Reservation.

During path computation process, communication resources may become congested (e.g., due to heavy usage). This condition makes it difficult for people with emergency activities to coordinate their efforts. Also, user may want to stop their lower-priority attempts and dedicate their end-system resources to high-priority ones. In order to improve emergency response, it is essential to prioritize access to resources during path computation.

The proposed mechanism defines two different priority types: *high priority* and *low priority*. When a request with higher priority arrives, it can undo pre-reservations of a lower priority in cases where the available resources are not sufficient. Resources are not preemptable, after allocating them. To prevent starvation of lower priority request, we define a threshold for undoing pre-reserved resources. We consider a constant value for threshold, but it can be set by network conditions and rates of service to higher and lower priority requests. In the following, we illustrate the pseudo-code of the resource reservation in two different priorities.

5. SIMULATION RESULT

In order to evaluate the performance of the proposed protocol, we implemented the path computation mechanism with domain sequence procedure and path computation flooding (PCF), in Opnet v.14 simulator [21]. For this purpose, a network topology as shown in Fig.5 is simulated.

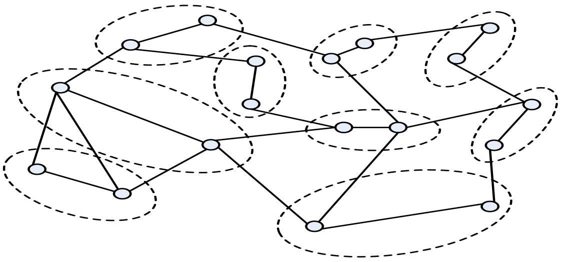


Figure 7. Network Topology.

The following parameters have been used to evaluate the proposed protocol.

- *Reply success ratio*
- *Network utilization*
- *Blocking rate of the requests*
- *Traffic load/network load*
- *Path cost*
- *Memory usage*

The PCE request success is the ratio of successful replies to the maximum number of requests. We define the network utilization as the ratio of the successful deployments to the maximum number of requests and network load is the maximum number of messages that can be moved in the network.

5.1. Implementing Domain Sequence Procedure

In order to assess the performance of the proposed mechanism, the network has been examined in two scenarios: At first, simulation parameters are evaluated only by considering hop count criteria. Then, we added delay to Qos metrics.

a) Implementing the Algorithm with Hop Count

Implementing this procedure will decrease the number of routes in network due to the pruning of the non- feasible and non-promising routes. As we have to pre-reserve resources in all of these routes in PCF method, by pruning we can decrease the number of reserved resources in network. So, these resources can be used by other requests that need them and this increases the resource availability in network. So, with this method we can service to the more requests and this will be increase the rate of successful replies (Fig.8) and decreases the blocking probability (Fig.9).

As seen, the obtained results in Fig. 10 and Fig. 11 show a relative improvement in network utilization and reduce the network load. Because in this case, we have more successful deployment of LSPs, and according to definition of the network utilization, this can increase the network utilization. On the other hand, the reduction in blocking causes to decrease the number of messages that resends. Resending the messages not only lead to increase traffic in network, but also influences the network performance. With pruning, we can decrease the number of unsuccessful requests. So, network load can decrease due to the reduction in resending the messages.

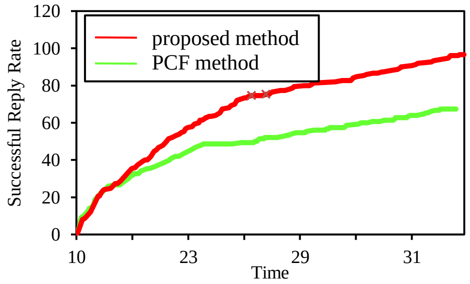


Figure8: Successful Reply Rate.

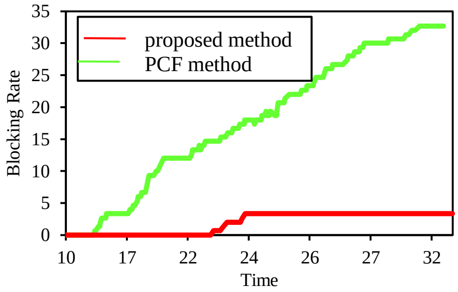


Figure9: Request Blocking Rate.

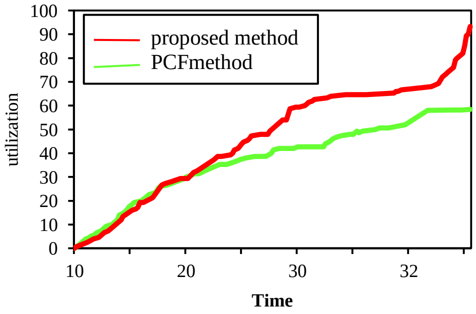


Figure10: Network Utilization.

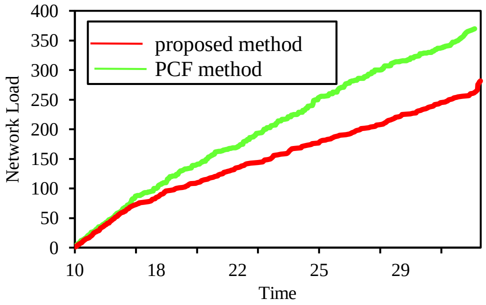


Figure11: Network Traffic Load.

In the proposed method, we have more resource availability in network. If we consider hop count as the path cost, resource availability can cause to select shorter routes. In particular, resource shortage in these routes may lead to select the longer routes. So, the average costs of the routes will be decrease by proposed method, Fig. 12.

b) Considering both Hop Count and Delay

In this section, two QoS metrics are considered in computing the path: *hop count* and *delay*. Fig.13 shows the number of resources that are reserved for two methods. As seen, considering two QoS metric in computation can help to have reduction in resource reservation. In particular, some paths cannot satisfy the requested delay. These paths will be omitted and their resources can be used by other requests. As a result, the ratio of successful replies increase (Fig. 14) and we have reduction in blocking rate (Fig. 15). All of these can help to improve network utilization, Fig. 16.

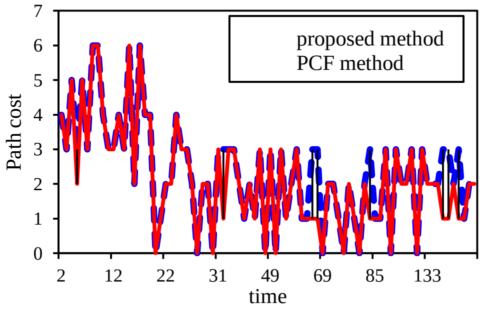


Figure12: Path Cost.

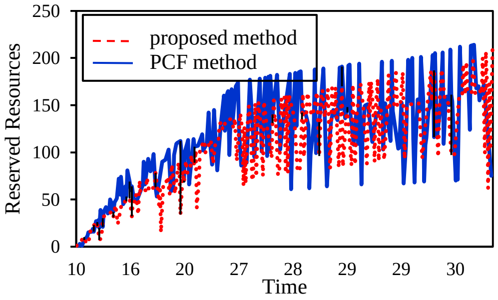


Figure13: Reserved Resources.

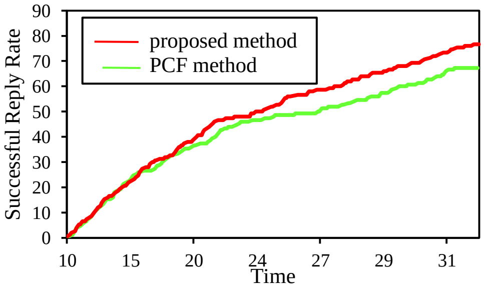


Figure14: Successful Reply Rate.

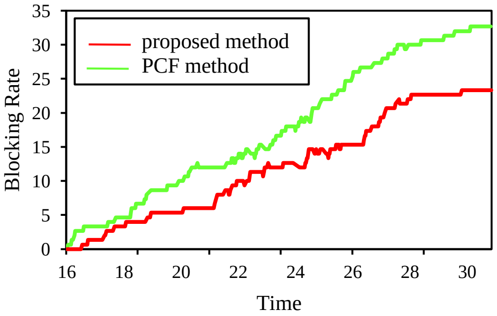


Figure15: Request Blocking Rate.

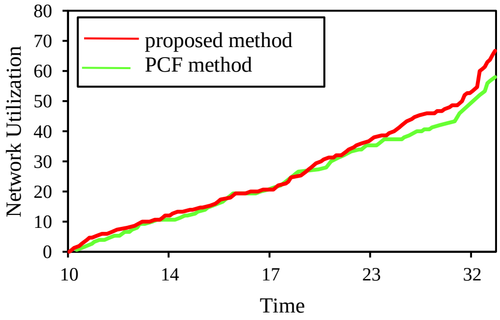


Figure16: Network Utilization.

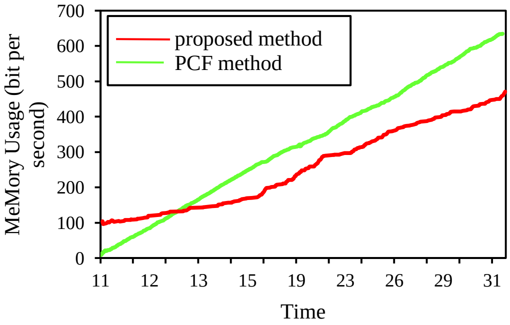


Figure17: Memory Usage.

5.2. Analysis the Memory Usage in Domain Sequence Procedure

In the proposed mechanism, we use “pruning method” for decreasing network load. As mentioned previously, this method needs a PCE to keep *ReqId* and *ReqCost* of the request messages. So, it can be argued that the proposed method needs more memory for recording the request’s information. But as seen in Fig. 20, memory usage in domain sequence procedure is lower than Path computation flooding. That’s because we prune routes in network and this reduces the amount of traffic. As a result we record the information in limited number of nodes and don’t need to record them in all of PCEs. On the other hand, we need to keep connection information and resource reservation while setting up a connection. Sorting connection establishment information requires local memory. In base method we have higher connections, so needs more memory for keeping the information. While in the proposed method, non promising routes will be deleted and we need lower Memory for keeping path setup information.

As seen in Fig. 17, at first we have higher memory usage in the proposed method due to the information that is recorded in PCEs. After a determined time, the algorithm starts pruning the routes. As the number of pruned routes increased by the algorithm, memory usage will reduce. Because the amount of path setup information that should be kept in base method is higher than pruning. This leads to more memory usage in the base method than proposed one.

6. CONCLUSION AND FUTURE RESEARCH DIRECTIONS

In this paper, we discuss the general issues of the PCE based path selection algorithms in multi-domain network. We also propose a procedure for finding domain sequences in PCE based path computation algorithms. Finally, we introduce a priority-based path selection procedure that facilitates emergency responses and avoids blockage at the time of TE-LSP deployment in multi domain networks. The proposed mechanism reduces the overhead of the network by means of a pruning mechanism that prunes non promising paths and only pre-reserves the promising ones. The simulation results give conclusive insight to the advantages of the proposed solution.

The results show that the proposed method increases the chance of the successful deployment of TE-LSP and decreases blocking probability without deteriorating the network utilization. To continue the work presented in this paper, a mechanism should be defined to dynamically change the weight factor α_i according to the network conditions. Future mechanism can investigate the consideration of QoS parameters other than the number of hops and delay. A mechanism can also be defined to dynamically find preempting threshold using network conditions and service rate of high and low priority requests. It is also interesting to relate the request priorities to the solution for the correct setting of pre-reservation timers.

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