New Dynamic Network Design and Provisioning Algorithms for Broadband Connection Services Considering Fairness

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Abstract— **We propose novel dynamic network control algorithms that reduce the blocking probability for dynamic bandwidth service provisioning. The expected network services include on-demand broad bandwidth provisioning services and layer one VPN. The important service attribute of fairness in terms of path length is effectively achieved by introducing a simple weighting function that considers path length and link utilizations of intermediate links of candidate paths. The algorithm achieves enhanced network utilization by rerouting existing paths to alternative routes without disruption. Numerical examples demonstrate that the developed algorithms attain not only a high degree of fairness but also low service blocking probability.**

I. Introduction

Due to the rapid penetration of broadband access, Internet traffic has been exploding throughout the world. In order to cope with this large increase in traffic demand, new optical transport systems employing wavelength routing via ROADMs (Reconfigurable Optical Add/Drop Multiplexers) have been widely deployed [1], [2]. Demands for IP/Ethernet-based (layer 2 and 3) virtual private network services are also rapidly increasing. This fuels the advancement of network control technologies based on ASON/GMPLS [3], [4]. Such developments are spurring carriers into providing new layer one services that offer dynamic and adaptive bandwidth for the creation of the cooperative utility backbone and that are necessary for wholesale carrier business [5], [6]. They include broad bandwidth on-demand provisioning services such as Optical Mesh Service provided by AT&T [7] and JiT (Just in Time) service by Verizon [5]. These VPN services require agile network reconfigurability. Ultra-high definition video (raw bit rate of 72 Gbps) and 4-k cinema (6 Gbps) distribution, and Grid-computing will also become the key services. Dynamic and adaptive bandwidth provisioning capability is a key to satisfy such broadband requests economically. The connection requests are likely to be more schedule-based (unlike sporadic telephone calls), and guaranteed bandwidths (in other words, guaranteed quality) need to be provided [5], [6]. To enable such emerging large-capacity services cost effectively and to meet diverse service requirements, novel dynamic network control technologies need to be developed. In the current approach to the provisioning of dynamic services, minimization of service blocking probability or good load balancing is taken as the criterion of network control. Based on this criterion, a path (in this paper, path is used interchangeably with circuit, since the service will, for example, use VC-3/4; SONET/SDH higher-order paths) is setup when a connection request is received. A comprehensive review of lightpath establishment can be found in [8]. Generally speaking, the routes of existing paths will not be changed while a connection is being made. However, since the traffic distribution keeps changing all the time, path assignment will slowly diverge from the optimal path accommodation. What is worse, it may not be possible to route new paths through congested areas. Re-optimization by rerouting existing paths in response to new demands is, therefore, necessary to attain lower blocking probabilities (higher network utilization).

The impact of rerouting has been discussed for circuit-switched telephone networks [9], [10]. It has also been recently introduced to optical WDM networks [11]-[14]. In [15], an analysis of rerouting in circuit-switched networks was provided; it verified that rerouting can significantly increase throughput compared to traditional dynamic routing. Rerouting for the provisioning of multi-granularity connections in optical WDM networks was also studied [14]. Some rerouting techniques were summarized in [16].

Rerouting is a simple operation that switches an existing path from its current route to another route. We can classify it into two strategies; *passive rerouting and intentional rerouting* [13]. Passive rerouting means reroute existing paths to accommodate new path requests which would otherwise be blocked. The basic idea of intentional rerouting is to intentionally reroute some existing paths to vacant routes in advance if it yields better load balancing. Latest studies focused not only on reducing the blocking probability or on achieving better load balancing, but also on reducing disruption time. For example, a rerouting scheme called *move-to-vacant wavelength-retuning* (MTV-WR) [11] has been proposed and achieves shorter disruption time and further studies have been published [12]-[14]. Most of the rerouting schemes developed so far generally cause path disruption; an existing path is disconnected before the alternative path is setup. Such disruption can significantly impair the quality of real-time applications such as live video

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streaming. To the best of the authors' knowledge, there has been no detailed study on hitless rerouting and its impact.

Another important attribute necessary for service provisioning is fairness. Service price for each connection will tend to be constant within a certain area irrespective of the connection length (node hop distance). Hence, rejection ratios should be as equal as possible among users of the same service level (or users belong to the same service level agreement) in the same area. In general, the blocking probabilities are unequal between long-distance and short-distance paths; long-distance paths traverse more nodes/links and so are more affected by other paths than the short-distance ones.

In this paper, we propose novel dynamic network control algorithms that can reduce the blocking probability, prevent service disruption, and improve fairness among users. In this paper, service bandwidth is assumed to be constant as a fundamental service, but bandwidth variations can be treated by extending the discussions made in this paper.

The reduction in blocking probability is achieved by rerouting, and the prevention of service disruption is attained by introducing the Make Before Break Routing (MBBR) technique [4]. In MBBR, the alternative path is setup before the existing path is disconnected for rerouting. Please note that the existing leased line service that realized hitless protection for digital paths in TDM uses one plus one protection where the protection path route is predetermined. It utilizes phase information of virtual containers in SDH [17] and this mechanism is also available in OTN (Optical Transport Network) [18]. In MBBR, on the other hand, the alternative route is determined dynamically. Hitless rerouting is thus possible with the MBBR mechanism. Regarding path rerouting, we propose two methods that have different levels of complexity. Finally, we show that fairness is effectively achieved by using a weighting function that considers path length and the probability of intermediate link occupancy in determining path routes. Numerical experiments confirm that the three objectives, i.e., reduction of blocking probability, prevention of service disruption, and improvement of fairness, are simultaneously achieved.

II. PRELIMINARIES

In this paper, we assume that the maximum number of paths/circuits, N, accommodated in a fiber is common to all fibers in the network. Path routing is done by PCEs (Path Computation Elements) [19] that have information on the network resources; topology, the number of fibers between each node pair, and current route assignments for all paths. Path connection requests are assumed to follow a Poisson process with an average arrival rate of ν. Holding time of each path follows a negative exponential distribution. The average holding time, h, of each path depends on the application and can range from a few hours to several weeks or more. It is assumed that at every fixed time period, Δt, the PCE setups new paths (see Fig. 1).

The network operation scenario consists of two stages; initial setup stage where traffic volume is small, and dynamic control stage. At the initial setup stage, we follow the accommodation algorithm that we previously developed and described in [20]; for given path demands, the shortest route is assigned to each path since no blocking is expected because traffic demand is small compared to the network resources reserved for the service. If multiple shortest routes exist, one of them is selected randomly. The dynamic control stage is summarized as follows.

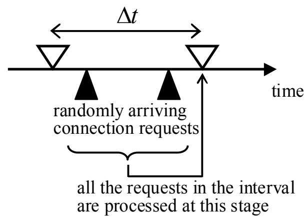

Fig. 1. Periodic path connect/disconnect operations

Dynamic Routing with Rerouting

Step1. Release resources of the paths disconnected in the last period.

Step2. Setup new paths whose requests arrived in the last Δt period.

Step3. Accommodate new paths.

Step4. If some new paths are blocked in Step3, we reattempt the accommodation of the blocked paths by rerouting some existing paths.

In Step2, we search for the shortest routes for the new paths using Dijkstra's algorithm [21]. This shortest path approach lessens the hindrance effect on other paths in later periods [20]. In Step3, we employ the accommodation method introduced in the next section to attain fairness. In Step4, we consider MBBR when existing paths can be rerouted, which is explained in Fig. 2.

Throughout the paper, algorithm performance is evaluated by blocking probability, p_B, as defined by the following equation

$$p_B = \frac{B}{A+B},$$

where B is the number of blocked connection requests in the dynamic control stage and A is that of successfully accommodated connection requests.

Remark: The relationship between h and Δt can be very different depending on the service. h can be a month or more and Δt can be one day or a week for virtual private network services; h can be a few hours and Δt may be less than one hour for the real-time video stream service.

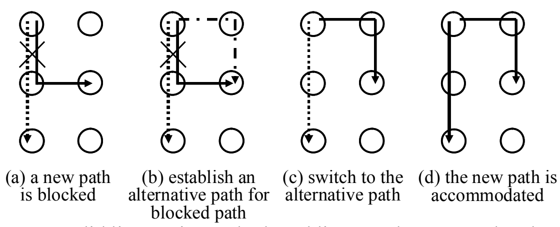

Fig. 2. Outline of MBBR

III. ROUTE ASSIGNMENT METHOD CONSIDERING FAIRNESS BETWEEN PATHS

In this section, we consider fairness in path establishment among path connection requests. Establishing long-distance paths is more difficult than establishing short-distance paths since the former can be more affected by the other paths. This results in non-uniform blocking probability and violates fairness. Hereafter we propose a simple but effective method to achieve fairness.

Suppose that blocking probability at a link is B and this probability is the same for all links. It follows that the probability of successfully accommodating a 1-hop connection is $1-B$ and the blocking probability of an n-hop connection is

$$B_{path} = 1-(1-B)^n . \quad (1)$$

If 1>>B, the probability in (1) can be approximated by

$$B_{path} \approx 1-(1-nB) = nB , \quad (1)'$$

and, therefore, B_{path} is proportional to the path length. Note that there are many route candidates for long-distant connections and we must take this fact into consideration in addition to (1)'. However, the number of route candidates strongly depends on the network topology. Accordingly, we introduce a new measure that represents the probability of link occupation by each connection. Let the number of hops of the shortest route(s) connecting nodes s and d be $h(s,d)$. The probability of link occupation $\rho(s,d)$ is estimated by

$$\rho(s,d) := h(s,d)/\#\{l(s,d)\} ,$$

where $l(s,d)$ stands for the set of links connecting nodes s and d, where such links are traversed by any one of the shortest paths. We then define a weighting function used in the following discussion.

$$W(s,d) := h(s,d)^w \cdot \rho(s,d) , \quad (2)$$

where parameter $0 \le w \le 1$ must be controlled to maximize fairness depending on the network conditions that include topology, traffic distribution, and so on.

For all connection requests that arrived during a period, we first assign a nonnegative constant to each of them where the constant is randomly selected from a closed interval. Next we multiply $W(s,d)$ defined in (2) by the constants. Then, in descending order of the constants, we try to establish a path route connecting the source and the destination of each request. This process realizes weighted random selection in path establishment for connection demands.

It is demonstrated in Sec. V that this relatively simple strategy can realize fairness with small computational cost.

IV. PROPOSED REROUTING ALGORITHMS

The establishment of path connection described in Sec. III fails if there are insufficient resources for all possible routes. First, we search for the route candidates, and then choose one according to the fixed criterion. For simplicity hereafter, we select route candidates in a random manner. Next, we try to create spare capacity from source to destination nodes to accommodate the request by rerouting some existing connections. The probability of successful rerouting strongly depends on the procedure used to search for the paths to be rerouted. In the following we propose two procedures to select and relocate paths.

A. MBBR Based on Local Search for Rerouting Paths (L-MBBR)

Suppose that a new path, p_{new}, can not be established because some links on its route are full. This method checks each link on the route from source to destination. For each full link l_f, let the set of all active paths that go through l_f be $P_{conflict}(l_f)$. We select a path p_c in $P_{conflict}(l_f)$ that holds the largest number of common full links with p_{new}. If there are multiple paths that achieve the maxima, then select one arbitrarily. Next, we derive an alternative route for p_c by applying Dijkstra's algorithm to the topology where link l_f is removed. Computational cost of this method is approximately proportional to the number of hops of the new path. This method has much shorter calculation time than the second method at the cost of lower performance.

B. MBBR Based on Global Search for Rerouting Paths (G-MBBR)

Suppose that a new path, p_{new}, can not be established because some links on its route are full. This method checks all links on the route simultaneously. Let $P'_{conflict}$ be the set of all paths going through some of the full links on the route. Among all subsets in $P'_{conflict}$, we select the one that minimizes the number of relocation operations. If there are multiple path sets that minimize the number of relocation operations, we select the one that minimizes the cost for rerouting defined by

$$C_{rerouting} = \alpha \cdot l + \beta \cdot t ,$$

where l is the total hop count of rerouted paths, and t is the sum of remaining holding time of paths to be rerouted. α and β are coefficients and $\alpha >> \beta$. The meaning of the second term of the right-hand side is as follows. The route length of the rerouted path will be longer than that of the original path in general, which causes inefficiency in resource utilization; the degree of the inefficiency is regarded to be proportional to remaining holding time. The profit gained by the rerouting (and thus establishing a new connection) is rather deterministic whereas the inefficiency of the rerouted paths is probabilistic. Thus, to consider both of these attributes with regard to cost, we introduce the weighting coefficients to provide the incentive of deterministic profit.

The computational cost of this method is approximately proportional to the exponential of the number of hops of the new path. This method requires much longer computational time than the first method, however, it provides much better solutions in terms of blocking probability.

The method in *A* is suitable for on-demand type services, and the method in *B* is effective for services with longer provisioning times.

V. NUMERICAL EXPERIMENTS

This section presents quantitative evaluations conducted to verify the effectiveness of our algorithms. The topologies examined were a 4x4 polygrid network (Fig. 3), Japan's national network (Fig. 4)[22], and COST266 network (Fig. 5)[23]. We assumed the following general conditions.

(a) randomly distributed traffic demands
(b) traffic loads are given by

$$L = L_{amp} \cdot L_{static} \, ,$$

where L_{static} stands for the average traffic volume used at initial setup stage and L_{amp} is a scaling factor that ranges from 0.7 to 1.2.
(c) each path has fixed capacity (ex. VC-3/4 in SDH)
(d) each fiber can accommodate 16 paths (N = 16)
(e) h is 4 hours and Δt is 2 hours
(f) ν is given by

$$\nu = L / h \, .$$

(g) hop slug, i.e. acceptable hop increment with rerouting, is set at 4.

In order to test the performance of the proposed algorithms described in Sec. III and Sec. IV, the following experiments were performed.

A. Degree of Fairness among Paths

We investigate the blocking probability of paths with different path lengths to evaluate the fairness among paths.

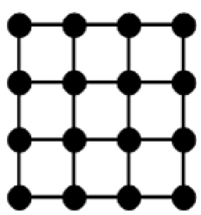

Fig. 3. 4x4 polygrid network

Fig. 4. Japan's national network

Fig. 5. COST266 network

Let x_i be the ensemble average of blocking probabilities of path requests between node pairs where the length of the shortest path connecting each pair is i-hop. To evaluate the attained fairness, we use Jain's Fairness Index [24] which is given by

$$f(x_1, x_2, \cdots, x_n) = \left(\sum_{i=1}^{n} x_i \right)^2 \Big/ n \sum_{i=1}^{n} \left(x_i^2 \right).$$

When the fairness index f is 1, the blocking probability is equal for all x_i. Fig. 6 shows the calculated fairness index f for different values of w. It is demonstrated that the most appropriate value of w depends on the topology, but by applying the proposed weighting function and selecting the appropriate w, fairness can be improved for any topology.

B. Blocking Performance Improvement Attained with MBBR and Impact of Rerouting Path Selection Methods

We evaluated the performance of the proposed methods described in Sec. IV by comparing them to a basic method where paths to be relocated are selected randomly (R-MBBR). The results are shown in Fig. 7, Fig. 8, and Fig. 9 for the three network topologies. They verify that rerouting improves the blocking probability substantially. For example when the target blocking probability is 10^{-3}, applying MBBR allows the maximum traffic load to be increased by more than 10 % for the topologies tested (for the 4x4 network it is more than 20 %, although this is not explicitly shown in Fig. 7). They also verify that G-MBBR is most effective in reducing the blocking probability; two to three orders of blocking probability improvement is attained when it is around 10^{-3} without MBBR.

In COST266 network, the hop increments of the k^{th} shortest paths to their shortest paths are smaller than those in the other two networks (the ratio is approximately 1/2~1/3). This means that the penalty for selecting alternative route in the rerouting stage is smaller in COST266 network and this would be the main reason why the difference between R-MBBR and proposed methods is smaller as shown in Fig.9.

C. Effect of Combination of Proposed Methods

We verify the performance of the integrated method that applies the weighting function described in Sec. III and G-MBBR in Sec. IV. Some results with L_{amp} = 1.0 are shown in Fig. 10 to highlight the fairness improvement. In this experiment the improvement in blocking probability is just 3-5 percent. As explained before, the probability of successful rerouting is higher for shorter new paths because the number of rerouted paths is smaller. However, by setting the parameter value of w in (2) at an appropriate value (in Fig. 10, w =1), it is demonstrated that the integrated method can improve fairness while decreasing the blocking probability.

D. Effect of Hop Slug and Traffic Demand Distribution

Blocking probability deviation in terms of hop slug variation is shown in Figs. 11-13. If the hop slugs are larger than four, the attainable blocking probability reduction is marginal. On the other hand, longer paths occupy more resources and larger hop slug results in higher computational cost since more path candidates will exist. Thus the hop slug should be small enough while still suppressing the blocking probability effectively.

We also found that the selection of the rerouting strategy has a significant impact on the blocking probability when we allow roundabout routes by the hop slug. When hop slug is larger than around four, G-MBBR reduces the blocking probability by approximately 50~67% compared to L-MBBR.

Figures 14 and 15 show the cases where the traffic distribution probability between each node pair is proportional to the product of the populations at the end nodes. Although the traffic distribution differs from the original, the blocking probability reduction characteristic is almost same as in the cases of uniform distribution. These evaluations confirm the effectiveness of the proposed method in general situations in terms of traffic distribution.

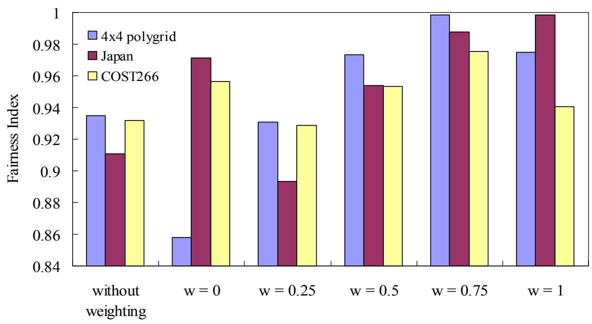

Fig. 6. Effect of weighting in three topologies: L_{amp} is 1.0, no rerouting

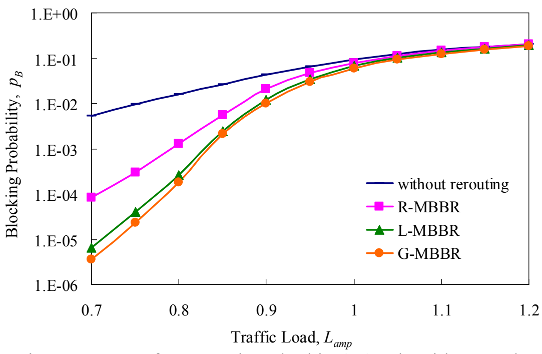

Fig. 7. Impact of proposed method in 4x4 polygrid network

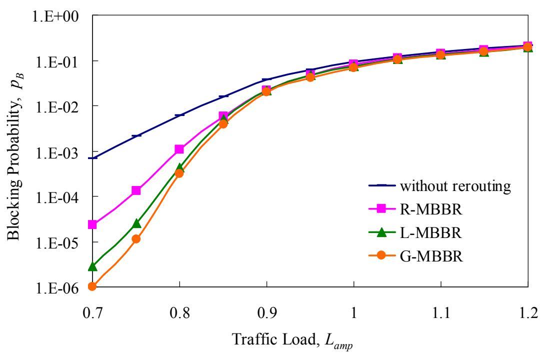

Fig. 8. Impact of proposed method in Japan's national network

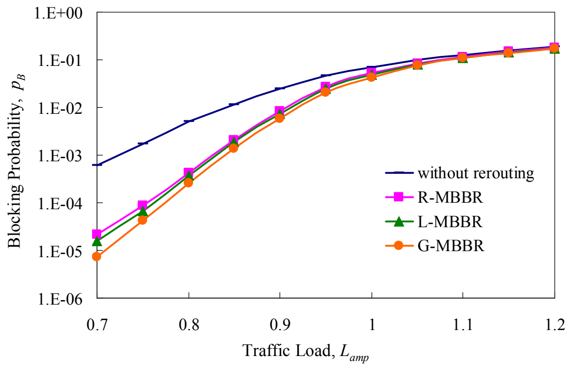

Fig. 9. Impact of proposed method in COST266 network

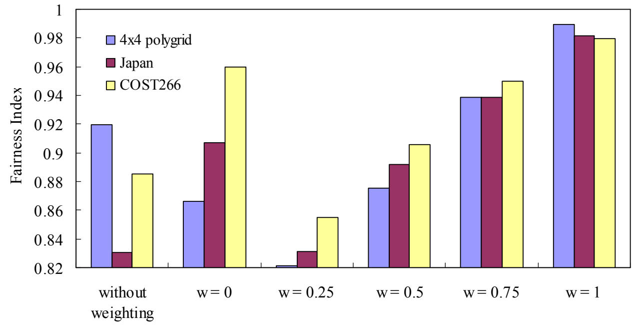

Fig. 10. Effect of weighting in three topologies: L_{amp} is 1.0, with G-MBBR

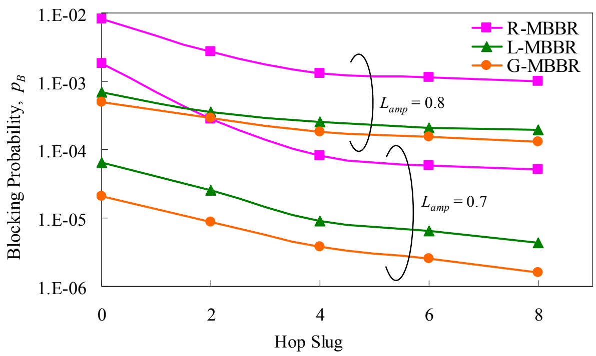

Fig. 11. Effect of hop-slug restriction in 4x4 polygrid network

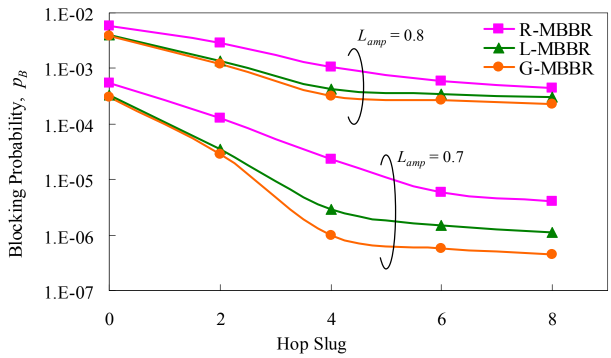

Fig. 12. Effect of hop-slug restriction in Japan's national network

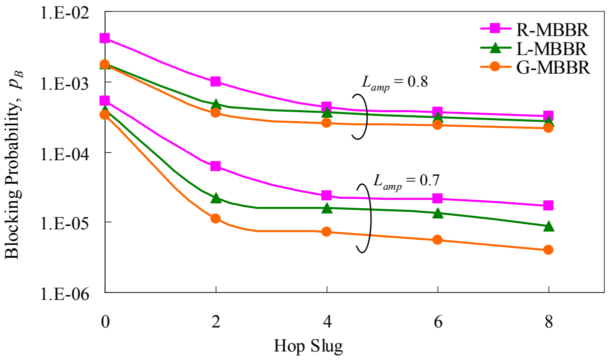

Fig. 13. Effect of hop-slug restriction in COST266 network

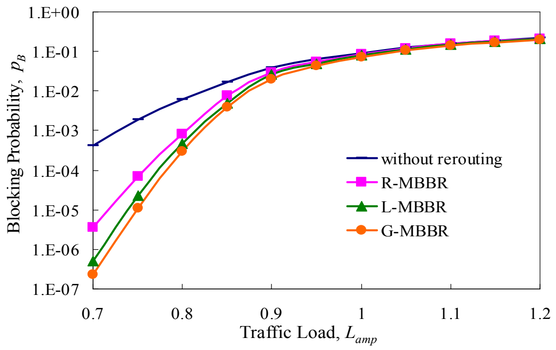

Fig. 14. Impact of proposed method in Japan's national network (Considering population distribution)

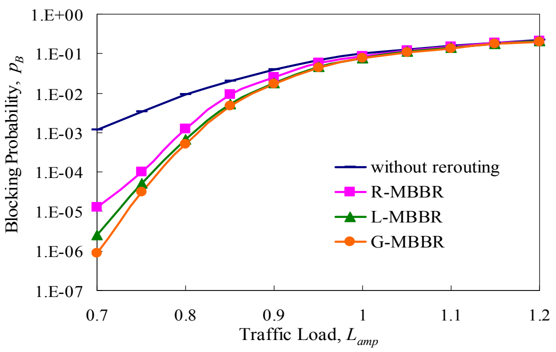

Fig. 15. Impact of proposed method in COST266 network (Considering population distribution)

VI. CONCLUSION

We proposed network control algorithms that enable schedule-based but dynamic bandwidth provisioning services using Path Computation Element. The important service attributes, low blocking probability (minimizing the network resources reserved), prevention of service disruption during rerouting, and fairness were discussed and solutions to these were presented. Numerical experiments using the developed algorithms demonstrated that they achieve not only fairness but also much lower blocking probabilities through their utilization of the make before break mechanism. The proposed algorithms will be effective in providing bandwidth-on-demand services.

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