Distributed Virtual Network Topology Control Mechanism in GMPLS-Based Multiregion Networks

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***Abstract*—This paper proposes a distributed virtual network topology (VNT) reconfiguration method for Internet protocol over wavelength-division-multiplexing network under dynamic traffic demand. We developed a simple heuristic algorithm for calculating the VNT for distributed control. Generalized multiprotocol label switching (GMPLS)-based routing protocol has been developed. The VNT is quickly reconfigured by setting up and/or tearing down lightpaths using GMPLS signaling protocol. Traffic demand is measured at the ingress node and advertised by the extended GMPLS routing protocol. Performance of the proposed method is investigated using variable traffic model.**

***Index Terms*—Generalized multiprotocol label switching (GMPLS), Internet protocol (IP) over wavelength-division multiplexing (WDM), topology reconfiguration, traffic engineering, virtual network.**

I. Introduction

THIS PAPER proposes a distributed virtual network topology (VNT) reconfiguration mechanism in Internet protocol (IP) over wavelength-division-multiplexing (WDM) networks. The IP over WDM network consists of a set of WDM-links and hybrid nodes, each of which consists of electrical IP router part and optical cross-connect pat. A lightpath is established between the hybrid nodes. A set of lightpaths provides a VNT to carry IP packet traffic offered to the network. Adequate VNT is configured for a given traffic demand. The number of wavelengths per link and the number of transceiver per node is a limited resource. The adequate VNT is determined under the limited resource constraint.

The VNT design problem has been extensively studied for a static traffic demand [1], [2]. The VNT can be designed for a given initial traffic demand. As the network grows, the traffic demand can significantly differ from the initially designed one. Reconfiguration of the VNT would be required to adapt such traffic demand change.

Several methods for reconfiguration of the VNT have been proposed [3], [4]. Those methods assume that the future traffic demand is given. Those methods aimed at the reduction of topology change in reconfiguration process. The new VNT is determined from the current one to adapt the given traffic demand. The traffic demand is hard to anticipate accurately in real networks. The traffic demand also fluctuates frequently in real networks. Traffic measurement and reconfiguration of the VNT should be orchestrated to cope with unpredictable traffic demand. A method for reconfiguration of the VNT under dynamic traffic demand change would be required to cope with unpredictable traffic demand.

Reconfiguration problem of the VNT under dynamic traffic is studied in a recent work [6]. The method uses an off-line algorithm for time-variant offered traffic. It assumes that a set of traffic matrices at different instants is known *a priori*. Another work on VNT under dynamic traffic includes an on-line reconfiguration method of the VNT [5]. The method monitors the traffic instead of assuming future traffic pattern. A simple adjustment to the VNT is applied to mitigate congestion and reclaim network resource for underutilized lightpaths if possible. The method is based on the centralized control, which collects the traffic demand measurement and calculates the new VNT for the obtained traffic demand measurement. The centralized controller initiates a lightpath setup/teardown procedure. A heuristic algorithm is used to calculate the VNT. A new lightpath is established between the end nodes of multihop traffic with the highest load using the most congested lighpath to mitigate the congestion.

This paper proposes a distributed VNT reconfiguration mechanism under dynamic unpredictable traffic. In distributed approach, each node decides whether it should initiate lightpath setup/teardown procedure. The distributed approach requires a mechanism for coordination between nodes. Unless the coordination mechanism is properly implemented, a new VNT might be formed inconsistently. The proposed method uses a link-state routing protocol for each node to share the same virtual topology and the traffic demand over the individual lightpath, which is measured at the originating node. Each node calculates the new VNT using a simple heuristic algorithm, compares it with the old one and initiates the lightpath setup/teardown procedure if necessary.

The rest of the paper is organized as follows. In Section II, we propose a distributed VNT reconfiguration method. In Section III, our protocol design based on generalized multiprotocol label switching (GMPLS) concept is explained. In Section IV, we investigate the performance of our method. In Section V, the conclusion is given.

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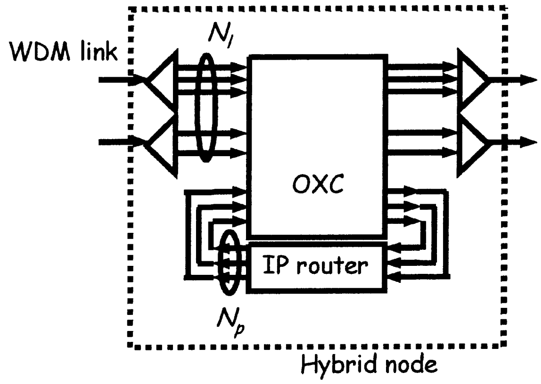

Fig. 1. Hybrid node architecture (unfolded view).

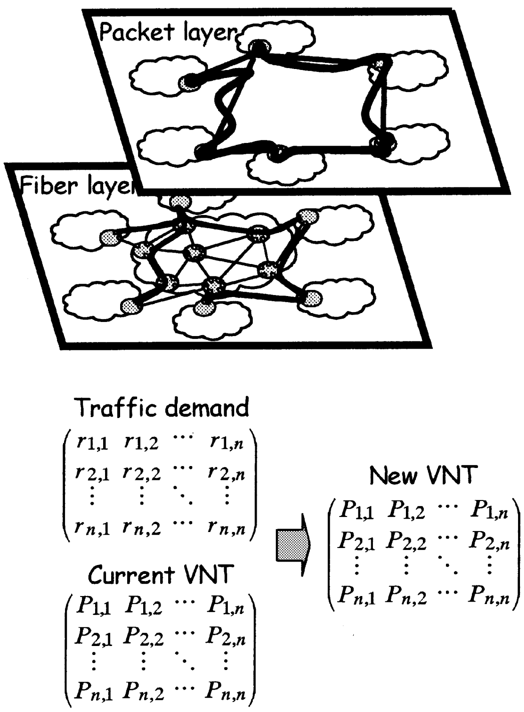

Fig. 2. Virtual network topology.

II. Proposed Method

A. Virtual Network Topology (VNT)

In this paper, we assume that a hybrid node, which consists of electrical IP router part and optical cross-connect (OXC) part is used (see Fig. 1). Every port of electrical IP router is connected to the OXC port via internal fiber. All traffic between nodes is carried over the WDM link. Some of them go to the electrical IP router part after it goes through OXC part and others go out the node through the OXC part. A lightpath is established between nodes by setting up the crossconnects along the route between nodes. The lightpath is terminated at the transceiver of electrical IP router part of end nodes. The number of wavelengths per link and the number of transceiver port per node is a limited resource in determining the VNT. Let Np and Nl denote the number of transceiver ports per node. Let w denote the number of wavelengths WDM links.

The VNT should be designed so that a set of traffic demand is efficiently carried (see Fig. 2). Let Λ denote traffic demand matrix, whose (i, j) element $\lambda_{\rm i,j}$ indicates traffic demand between node i to node j. The adequate VNT is determined for a given traffic demand matrix under the constraint of the number of wavelengths and the number of transceiver ports.

B. Design Goal

We raised three goals in designing our method. First, the method should be simple. Simple method means quick responsiveness. It is also easy to implement. Second, the method should be efficient. The goal of traffic engineering is to optimize network resource utilization. So the method should be efficient in terms of network resource utilization. Third, the method should work as a distributed system to achieve robustness against failure. It works automatically with minimum human intervention.

In the VNT reconfiguration process, we avoid centralized coordination by using a special class of VNT calculation algorithm. Two issues need to be addressed in designing the distributed method for the VNT reconfiguration. The first one is the order of lightpath setup and/or teardown and the second one is the conflicting requests on lighpath: one requests teardown of a lightpath while the other requests persistent use of the lightpath. These issues are easily resolved by a centralized method because the centralized method does not permit a change of lightpaths through reconfiguration unless it resolved beforehand using centrally maintained network database.

The first issue stems from the fact that the different virtual network topologies are obtained if we change the order of lightpath setup/teardown. If two nodes assume different order of lightpath setup/teardown, they have inconsistent views of the new VNT. In calculating the VNT, the order of the lighpath setup/teardown is fixed: the new lighpath setup is tried in the descending order of its traffic load to determine the route while the existing lighpath is torn down in the ascending order of its traffic load. We should note that we do not fix the “actual” order of setup/teardown even though we fix the “calculating” order of setup/teardown.

The second issue stems from the fact that one node may request to tear down an underutilized lightpath while the other may maintain it for quality-of-service (QoS) concerns. In this situation, these two nodes have inconsistent views of the VNT. This can be caused by different algorithms used in these two nodes.

C. Overview of Proposed Method

In the proposed method, each node uses the same virtual topology reconfiguration algorithm and such conflicting request cannot occur. Each node periodically measures the traffic carried over the lightpath originating from the node. If the measured traffic change in a measurement cycle, a link-state advertisement (LSA) packet carrying the traffic measurement data is flooded throughout the network. If the traffic carried over a lightpath exceeds the high threshold (T_H), each node initiates a VNT reconfiguration procedure. Each node calculates a better VNT to quell the congestion. In addition, the underutilized lightpath should be torn down if possible for future lightpath setup request. If the traffic carried over a lightpath becomes under the lower threshold (T_L), the lightpath is torn down only if a new congestion would not occur. This test is perfomed assuming if all underutilized lighpaths were removed. If the teardown of lighpath could cause a new congestion, it is not torn down. Comparing the better VNT and the existing one, each node identifies which lightpaths need to be set up and/or torn down. If the node is the one, from which the new lightpath is originating, it initiates a lightpath setup procedure. On the other hand, if the node is the one, from which the existing lightpath is originating, it initiates a lighpath teardown procedure. Each node performs the above tasks independently. No centralized coordination mechanism is required.

The proposed method measures traffic demand periodically. If the burst transfer period is much shorter than the measurement cycle, the traffic increase is not detected and the virtual topology reconfiguration is not initiated. For short burst transfer, optical burst switching approach is a promising approach. In the optical burst switching, the ingress node has a burst detection mechanism to initiate a lightpath setup procedure. Even though the virtual topology reconfiguration approach is more suited for time scale longer than midterm, burst detection mechanism could be incorporated into the proposed virtual network reconfiguration method to cope with short burst transfer. In addition, short-term traffic fluctuation need to be smoothed out for stable control. Low-pass filter is used for this purpose [13]. Maximum instantaneous utilization during a measurement cycle is regarded as a traffic demand.

D. Distributed Control Mechanism

Our method works as a distributed system. Each node in the network initiates the VNT reconfiguration procedure without centralized coordination. The key component of the distributed mechanism is to use a link-state routing protocol for each node to share the same virtual topology and the traffic demand over the individual lightpath, which is measured at the originating node. The link-state routing protocol is used to flood information on the VNT and traffic demand over the lightpath throughout all nodes in the networks.

Once the information on the VNT and traffic demand over the lightpath is shared by all nodes, identical VNT calculation algorithm is employed. After each node calculates the next VNT and compares it with the current one to identify which lightpaths should be set up and torn down, it starts to the procedure for lighpath setup/teardown if it is the originating node of the lightpath (see Fig. 3). The VNT is reconfigured after each node finishes setting up and tearing down the lighpaths. Once the new VNT is achieved, the IP traffic is rerouted over the new VNT.

To minimize disruption in tearing down lightpath, the lighpath is advertised as a dormant state by the originating node using the link-state routing protocol. When a node receives the link-state of dormant link, it detours all IP traffic around the dormant link. After the originating node confirm that no IP traffic is carried over the lightpath, it tears down the dormant lightpath.

The distributed method is extending a link-state protocol. All link-states in the network need to be shared by all nodes. The larger the network size, the larger the number of link-states. For a large scale network, a hierarchy could be used to achieve scalability. On the other hand, the network utilization could be compromised due to suboptimality of hierarchical approach.

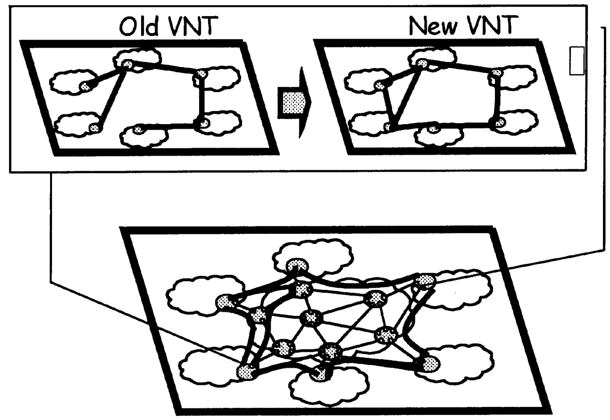

Fig. 3. Distributed control.

E. Heuristic Algorithm for VNT Calculation

A heuristic algorithm is used for calculating the VNT because it is simple enough to work quickly. In order to make the method work in a distributed manner, we do not assume any order of setup/teardown of lightpaths in designing the VNT calculation algorithm.

The algorithm adds new lightpaths to mitigate congestion and removes existing underutilized lightpaths if possible for reclamation. The VNT algorithm should not assume any order of setup/teardown of lightpaths initiated by individual originating nodes. Multiple new lightpaths may contend the same resource of the number of wavelength links and the number of transceiver ports before all underutilized lightpath candidates are removed. To avoid this situation, the heuristic algorithm adds new lightpath candidates first without relying on resources returned by removed lightpaths, and then removes existing underutilized lightpaths.

The heuristic algorithm uses two parameters to define congested and underutilzed lighpath: T_H and T_L denote thresholds for congested and underutilized lightpaths. Pseudocode for the lightpath addition part of the heuristic algorithm is given in Fig. 4. If traffic demand over the lightpath is greater than T_H, a new lightpath is set up to make traffic over the congested lightpath rerouted. End nodes of the new lightpath are selected among the adjacent nodes of the end nodes of the congested link and the end nodes of the congested link. The ingress node v_{ingress} and egress node v_{egress} of the new lightpath are selected such that sum of traffic demand from v_{ingress} to the ingress node of the congested link and from the egress node of the congested link to v_{egress} are maximized. The ingress node of the congested link can be v_{egress}. The egress node of the congested link can be v_{ingress}.

Pseudocode for the lightpath deletion part of the heuristic algorithm is given in Fig. 5. If traffic demand over the lightpath is less than T_L, it is torn down for reclamation if possible. It is torn down only if a new congestion would not occur after it is removed. All underutilized lightpaths are tested in a deterministic order in calculating the new VNT. We should note that even though we assume the deterministic order of lightpath deletion in the VNT calculation, we do not have to care about the order of lightpath teardown after the new VNT is determined.

```
AddLightpath(){
Route(TrfMtx);
for (int i=0; i<size; i++) {
 for (int j=0; j<size; j++) {
  if (i!=j) {
   if (uB[i][j]>TH*cap[i][j]) {
    for (int k=0; k<size; k++) {
     if ((PortAvailable(k)==true)
         && ((k!=i && LighPath(k,i))
         || (k==i))){
       for (int l=0; l<size; l++) {
         if (((k!=i) || (l!=j)) && (l!=k)
             && (PortAvailable(l))
             && ((j!=l && LightPath(j,l))
                 || (j==l))
             && (NoLightPath(k,l))) {
          if (uB[k][i]+uB[j][l]>=max) {
            max = uB[k][i]+uB[j][l];
            Src = k;
            Dst = l;
          }
        }
     }
     SetupLightPath(Src,Dst)
    }
   }
}
```

Fig. 4. Pseudocode for the lightpath addition part of the heuristic algorithm.

```
void removelink(){
route(TrfMtx);
for (int i=0; i < size; i++) {
 for (int j=0; j < size; j++) {
  if (i != j) {
   if ((uB[i][j] < TL*cap[i][j])
       && isRemovable(i,j)) {
       int Src = i;
       int Dst = j;
       removeNominalLambdaPath(Src,Dst);
       if (checkRoute(TrfMtx)) {// no
congestion
          removeLambdaPath(Src,Dst);
       }
    }
   }
  }
 }
}
```

Fig. 5. Pseudocode for the lightpath deletion part of the heuristic algorithm.

III. Protocol Design

A. GMPLS Architecture

Recently, GMPLS has attracted much attention from industry and academia. Intelligent IP routing technique is applied to various kinds of switching networks such as SDH/SONET, wavelength switch, and fiber switch. GMPLS provides a powerful blend of optical transport and IP routing (see Fig. 6), [7], [8]. GMPLS provides a powerful set of control mechanisms for multilayer label-switched path (LSP) networks composed of IP, SDH/SONET, lambda, and fiber layers.

GMPLS provides a framework for multilayer LSP network control. In the multilayer LSP network, a set of the lower-layer LSPs serves as the VNT for the upper-layer LSPs. For example, a set of wavelength LSPs serves as the VNT for the LSPs in IP/multiprotocol label switching (MPLS) packet layer. The fiber network topology is used as the VNT for routing the WDM-layer LSP, which in turn serves as the VNT for routing the IP-layer LSP. The VNT is reconfigured by setting up and/or tearing down WDM-layer LSPs in WDM-layer using the GMPLS signaling protocol. Traffic demand in IP-layer is disseminated by the GMPLS routing protocol extensions. Each node calculates the adequate virtual topology to meet the IP-layer traffic demand in a distributed manner. Each node initiates the path setup/teardown requests after comparing the new and old virtual network topologies.

In GMPLS architecture, a link-state routing protocol is used for topology discovery. Each node advertises a link state including all links originating from the node. The residual resource on the link is also carried in the link state. The link state is flooded throughout the entire network. When a node sets up the LSP to a destination, it calculates the feasible route for the LSP by running the constraint-based shortest path first (CSPF) algorithm. If the feasible route is found, the node initiates the LSP setup procedure.

1) Forwarding Adjacency in Multilayer Path Network: Multilayer path network control mechanism introduced by GMPLS plays a key role in the proposed distributed VNT reconfiguration. GMPLS introduces the concept of "forwarding adjacency (FA)" to control multilayer path networks [7]. In multilayer network, the lower-layer LSP is used for forwarding the upper-layer LSP. If two nodes are directly connected by a lower-layer LSP, they are regarded as being in the sate of "FA" in the upper layer. Optical LSP (i.e., lightpath) is set up first before electrical packet LSP is set up. Once the optical LSP is established, it is advertised by routing protocol as "FA-LSP" to allow packet LSPs to use it for forwarding. Setup or teardown of LSPs triggers the change of virtual topology for the upper-layer LSP network. In this way, FA-LSP enables us to implement multilayer LSP network control mechanism in a distributed manner. In multilayer LSP networks, the lower-layer LSPs form the virtual topology for the upper-layer LSP. The upper-layer LSP is routed over the virtual topology.

2) Switching Capability: Switching capability concept is introduced in GMPLS protocol to support various kinds of switching technologies in a unified way. Five classes of switching capability are defined: packet switch capable (PSC), layer-2 switch capable (L2SC), TDM capable (TDM), lambda switch capable (LSC), and fiber switch capable (FSC) [7]. Each end of the link in GMPLS network is associated with at least one switching capability. PSC is associated with interface which can delineate IP/MPLS packets (e.g., LSR's interface) while LSC is associated with the interface which can switch

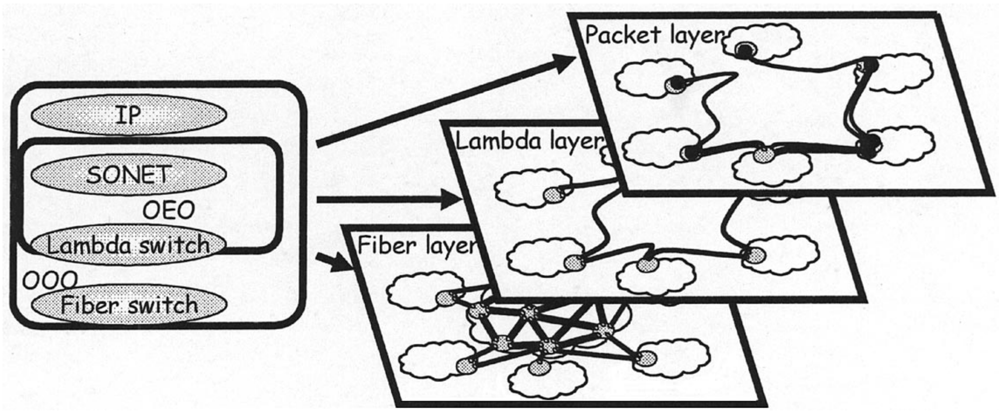

Fig. 6. GMPLS-based multiregion network.

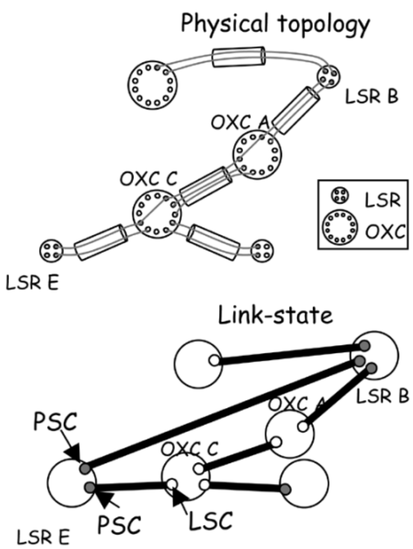

Fig. 7. Switching capability.

individual wavelengths multiplexed in a fiber link (e.g., OXCs interface). Every link in the link-state database has switching capabilities on both ends.

Switching capability is used to implement multilayer routing. Optical LSP is routed over the topology composed of link state, either of whose ends is LSC. In Fig. 7, optical LSP is routed from LSR-B, OXC-A, OXC-C, and LSR-E. The path for the optical LSP is composed of links, either of whose ends is LSC. Once the optical LSP is set up, it is advertised as FA-LSP [7], both ends of which are PSC. In calculating the path for packet LSP, link-state database is filtered to include the link, both ends of which include only PSC. In this way, hierarchical routing of packet LSP and optical LSP is done by using link-state database filtered with respect to switching capability.

The lower-layer (optical LSP) network provides the VNT to the upper layer (packet LSP) network. VNT is configured by setting up or tearing down optical LSPs in the lower layer. By using GMPLS signaling and routing protocol, the VNT can be altered easily. By changing the VNT, we can implement traffic engineering. The lightpath topology is altered to adjust the traffic demand of the IP layer.

B. Protocol Extensions

In our scheme, each node runs the VNT calculation algorithm, which requires the current virtual topology and the traffic demand of the packet LSPs. The information on traffic demand of the packet LSPs need to be advertised. The GMPLS link-state routing protocol [12] is extended to include the traffic demand information.

We need to avoid disruption when the optical LSP is released. The packet LSPs need to be rerouted before the underlying optical LSP. To advertise the optical LSP as dormant, the GMPLS routing protocol is extended. Once each node receives the dormant link state, it reroutes the packet LSPs over the dormant optical LSP to other nondormant optical LSPs. After all packet LSPs are rerouted, the dormant optical LSP is torn down. In this way, the graceful teardown of LSP is implemented in a distributed manner.

IV. Performance Evaluation

A. Effect of Dynamic VNT Change

We investigate the effect of the multilayer traffic engineering method using a sample network model. The BXCQ method is used in calculating the virtual topologies for optical and electrical layers [9]. The same network model as used in [9] is used. The network model consists of 11 nodes. We calculate the VNT producing the local optimum network cost. The network cost consists of optical layer cost and electrical layer cost. We assume that the optical layer cost is proportional to the number of LSC ports and the electrical layer cost is proportional to the number of PSC ports. Let α and β denote the cost of an PSC port and that of a LSC-port. We assume that an optical LSP has a fixed capacity of 2.4 Gb/s (It is determined by the capability of tranceiver at both ends of optical LSP). We assume that there is symmetrical traffic demand. Traffic demand between all source–destination (SD) node pairs is identical. We introduce a performance measure called the average nodal degree to characterize the VNT. The average nodal degree is defined as the average number of (virtual) links originating from the node. If we have 11 nodes in the virtual network, the fact that the average nodal degree is 10 implies that the virtual network is a full-mesh network.

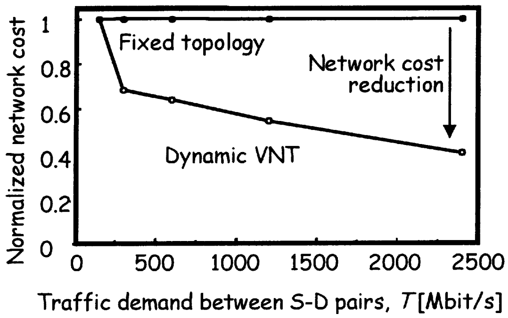

Fig. 8. Network cost as a function of traffic demand of SD pair.

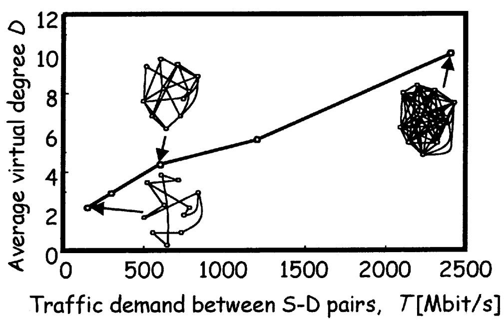

Fig. 9. Average virtual degree as a function of traffic demands backed up by wavelength.

1) Cost Saving Effect: Effect of dynamic topology reconfiguration is evaluated. The network cost is calculated for both fixed topology and dynamic topology change. Network costs with fixed topology and variable topology are compared. Fig. 8 shows the network cost as a function of traffic demand of SD pair. We assume that the optical LSP has fixed capacity of 2.4 Gb/s, the same as OC48c/STS-16. The network topology optimized when the traffic demand is 150 Mb/s is used for the fixed topology. As the traffic demand increases, the network cost is reduced with variable topology. The dynamic topology configuration reduces the network cost by half (see Fig. 8). We confirm that the traffic engineering method based on the virtual topology reconfiguration is effective.

2) Virtual Degree: We investigate the VNT for different traffic demand. Fig. 9 shows the relationship between the optimum average nodal degree of optical LSPs virtual topology and the traffic demand between SD node pair. The average virtual degree is defined as the average number of links originating from a node in the VNT. Two means that the VNT is close to ring while ten means that it is close to mesh for the physical network consisting of 11 nodes.

We observe that the optimum average nodal degree increases as the traffic demand between SD node pair. The average virtual degree is close to two when the traffic demand is small while it is close to ten when the traffic demand is large. This result agrees with the following observation. When the traffic demand is small, it is economical to aggregate the individual traffic demand between several SD node pairs into a single optical LSP. When the traffic demand increases, the number of SD pairs carried by a single optical LSP is reduced and the direct optical LSP is used to carry the fat traffic demand between SD node pair. From this result we confirm that our approach, which uses the direct optical LSP for the heavier SD node pair is effective.

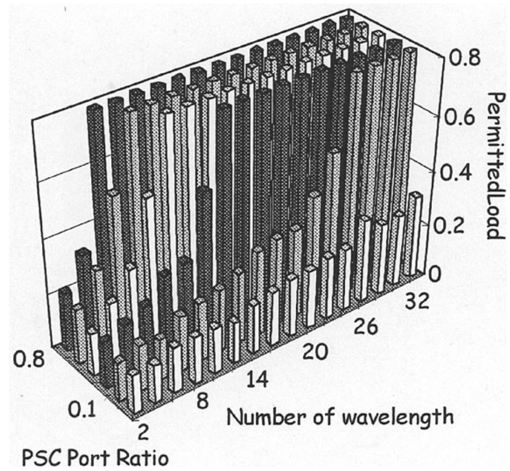

Fig. 10. Permitted load obtained by heuristic algorithm.

B. Utilization

The number of wavelengths per link and the number of transceiver port per node is a limited resource in determining the VNT. We investigate the impact of the number of wavelengths per link and the number of transceiver ports on the utilization. Recall that Np and $N\mathrm{l}$ denote the number of transceiver ports per node. Recall that w denote the number of wavelengths WDM links. We used the NSF network model consisting of 14 nodes and 25 links as used in [1]. The adequate VNT is determined for a given traffic demand matrix under the constraint of the number of wavelengths and the number of transceiver ports. Recall again that Λ denote traffic demand matrix, whose (i, j) element $\lambda_{i,j}$ indicates traffic demand between node i to node j. We assume that $\lambda_{\mathrm{i,j}}$ is uniformly distributed in the range $[0, r_1]$. We evaluate the maximum permitted load $r_{\max} = \max r_1$ obtained by our VNT reconfiguration method using bisection method. We assume that $T_H = 0.8$ and $T_L = 0.1$.

Fig. 10 shows that the permitted load as a function of the number of wavelength links w (=$2, 4, 6, 8, 10, 12, 14, 16, 18, 20, 22, 24, 26, 28, 30, 32$) and the PSC port ratio defined as $Np/N\mathrm{l}$ (=$0.1, 0.2, 0.4, 0.6, 0.8, 1.0$). As shown in Fig. 10, the permitted load increases as the number of wavelength or the PSC port ratio increases. In this network model with the physical degree and the average length of the shortest path between all nodes, when the number of wavelengths is moderate (between two and four), increase of PSC port ratio does not contribute the permitted load improvement. Shortage of wavelength resource limits the utilization in this region. As the number of wavelengths increases, increase of PSC port ratio improves the permitted load significantly.

C. Dynamic Traffic Change

We investigate how the traffic fluctuation affects the performance of our method. We assume that $T_H = 0.8$ and $T_L = 0.4$. We assume that the number of wavelengths $w = 24$ and the PSC port ratio $Np/N\mathrm{l} = 0.2$. We used three sets of traffic demand

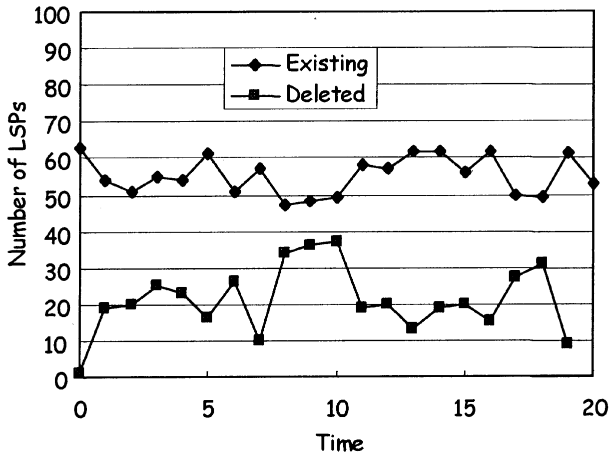

Fig. 11. Number of lightpaths as a function of time sequence: $(r_0, r_1) = (0, 0.3)$.

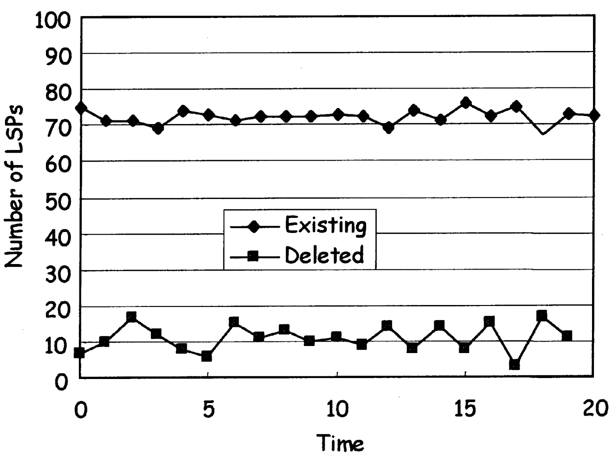

Fig. 12. Number of lightpaths as a function of time sequence: $(r_0, r_1) = (0.1, 0.2)$.

matrices. Each set has 20 traffic demand matrices randomly generated in sequence. We assume that $\lambda_{\mathrm{i,j}}$ is uniformly distributed in the range $[r_0, r_1]$. We used three sets of traffic demand matrices with the same average load (=0.15): $(r_0, r_1) = (0, 3), (0.1, 0.2)$, and $(0.125, 0.175)$.

The numbers of added and deleted optical LSPs in each seaquence are calculated. The maximum and average load of optical LSPs are calculated. Figs. 11–13 show the number of optical LSPs as a function of time sequence. The numbers of existing and deleted optical LSPs are depicted. By comparing Figs. 11–13, the number of deleted optical LSPs is moderate for less variable traffic $(r_0, r_1) = (0.125, 0.175)$ while it increases for variable traffic $(r_0, r_1) = (0, 3)$. Figs. 14–16 show the maximum and average load of optical LSPs as a function of time sequence. Maximum load of optical LSPs is controlled below the congestion threshold (T_H). Average load of optical LSPs is fluctuated around 0.3–0.4. It is less fluctuated as the traffic variability reduces (Compare two cases: $(r_0, r_1) = (0.125, 0.175)$ and $(r_0, r_1) = (0, 0.3)$).

The reconfiguration frequency is affected by the high and low thresholds for congestion and underutilization detection. We evaluated the effect of the thresholds on the frequency of the reconfiguration of the VNT. We evaluated average number of

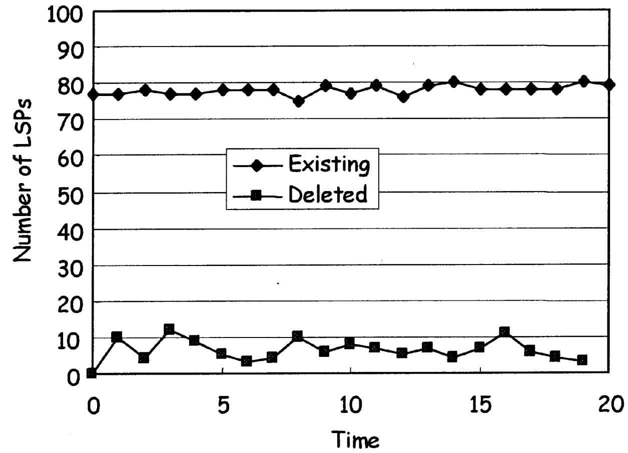

Fig. 13. Number of lightpaths as a function of time sequence: $(r_0, r_1) = (0.125, 0.175)$.

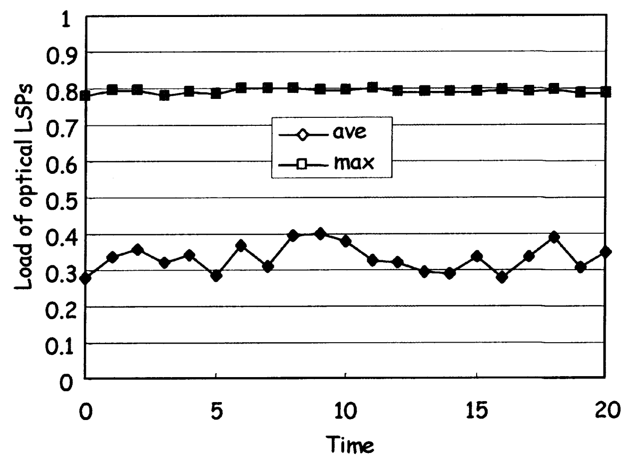

Fig. 14. Load of optical LSPs as a function of time sequence: $(r_0, r_1) = (0, 0.3)$.

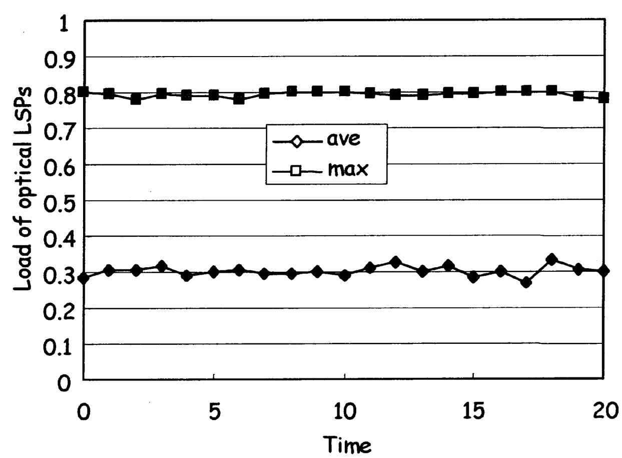

Fig. 15. Load of optical LSPs as a function of time sequence: $(r_0, r_1) = (0.1, 0.2)$.

optical LSPs under variable traffic condition, where 100 traffic demand matrices were randomly generated in sequence. Each element of traffic demand matrices is randomly distributed in the range of $(r_0, r_1) = (0, 0.3)$.

Fig. 17 shows that the relationship between the threshold for congestion (T_H) and the number of optical LSPs. When the T_H

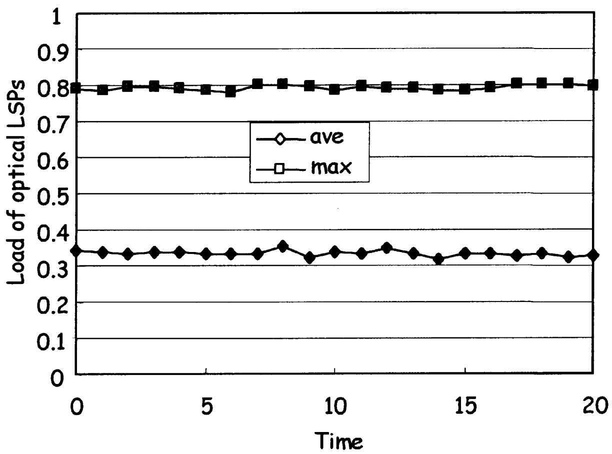

Fig. 16. Load of optical LSPs as a function of time sequence: $(r_0, r_1) = (0.125, 0.175)$.

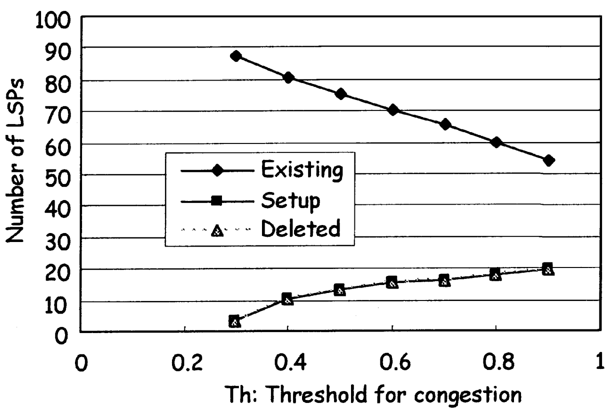

Fig. 17. Relationship between the threshold for congestion and the number of optical LSPs.

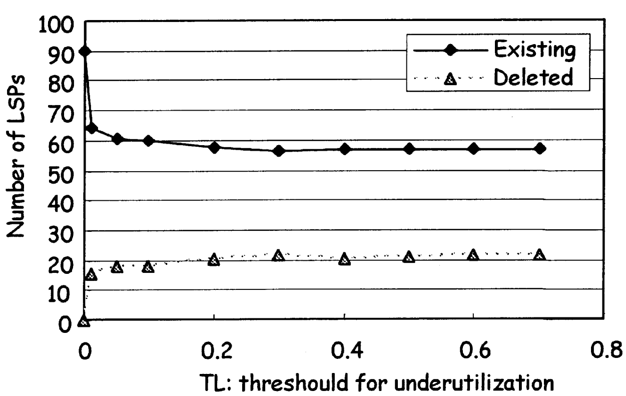

Fig. 18. Relationship between the threshold for underutilization and the number of optical LSPs.

is small, the number of existing optical LSPs is large because new optical LSPs are created to reduce the traffic load over the optical LSPs. As the T_H becomes larger, the number of existing optical LSPs becomes small becomes each optical LSP accommodate much more traffic demand.

Fig. 18 shows that the relationship between the threshold for underutilization (T_L) and the number of optical LSPs. When the T_L is small, the number of deleted optical LSPs is small. The number of existing optical LSP is large because the underutilized optical LSP is not released. As the T_L becomes larger, the number of deleted optical LSPs becomes large and the number of existing optical LSPs becomes small because the underutilized optical LSP is released.

In deleting optical-LSPs, traffic could be disrupted. In the proposed method, when the optical-LSP is torn down it is advertised as dormant so that each node can have the electrical-LSPs rerouted around the dormant optical-LSP. Electrical-LSPs are rerouted using "make-before-break" technique to minimize the packet loss during the switching process. After all electrical-LSPs get rerouted around the optical-LSP, it is actually torn down. In this way, the disruption is minimized.

V. Closing Remarks

In this paper, we proposed a distributed VNT reconfiguration method for unpredictable variable traffic demand. We developed a simple heuristic algorithm for calculating the VNT just requiring traffic demand carried over the existing lambda paths. The lightpath is set up to mitigate congestion and the underutlized lighpath is torn down for future traffic demand after confirming any congestion not occurring.

GMPLS-based protocol design is presented. Standard GMPLS routing protocol is extended to carry the traffic demand over LSPs so that each node can share the same traffic demand information. Identical information on both topology and traffic demand are shared by all nodes. Each node autonomously calculates a new VNT and decide whether it should initiate procedure for LSP setup and teardown without global coordination.

Performance of the proposed VNT calculation algorithm is investigated in light of the number of wavelengths and transceiver ports per node. Impact of traffic variability on the distributed virtual network reconfiguration is investigated.

We have completed development of prototype system of the proposed method. We will report on implementation and experimental results using actual system in the near future.

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