On the Stability of Virtual Network Topology Control for Overlay Routing Services

(Invited Paper)

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Abstract— **Overlay networks achieve new functionality and enhance network performance by allowing routing to be controlled at the application layer. However, these approaches result in degradations of underlying networks due to the selfish behavior of overlay networks. In this paper, we investigate the stability of virtual network topology (VNT) control under the overlay networks that perform dynamic routing updates. We reveal that the dynamics of routing on overlay networks causes a high fluctuation in the traffic demand matrix, which leads to significant instability of VNT control. To overcome the instability induced by the overlay routing, we introduce *hysteresis* to the VNT control. Simulation results indicate that the hysteresis mechanism improves the network stability, but cannot always improve the network performance. We therefore extend the hysteresis mechanism and show that the proposed method improves both the network stability and the performance when the amount of traffic for overlay network is not large.**

I. INTRODUCTION

Wavelength Division Multiplexing (WDM) technology, which carries multiple wavelength channels on a single fiber, is expected to carry a huge amount of traffic in the current and future Internet. Since the majority of Internet traffic is IP, much research has been devoted to methods of carrying IP packets over a WDM network [1]–[7]. One approach to accommodate IP traffic on a WDM network is to establish a set of optical transport channels, called lightpaths, between IP routers via optical cross-connects (OXCs). These lightpaths and IP routers form a *virtual network topology* (VNT) and IP traffic is transmitted over this VNT. To achieve the effective transport of IP traffic, VNT control, which configures the virtual network topology based on the traffic demand, has been studied in many papers [8], [9].

Overlay networks have recently received much attention as a way to realize new functionality or enhance network performance over IP networks. One of the key technologies in overlay networks lies in overlay routing [10], [11]. The fundamental idea of overlay routing is to construct a logical network on top of the IP network and to allow routing to be controlled on that logical topology[1]. Each overlay node measures status, such as throughput and delay, of the underlying network, and determines the appropriate route to destination nodes on the overlay network to improve the performance and resilience. The resilient overlay network (RON) architecture is proposed in [10]. RON provides fast detection and recovery from network failures or performance degradation using the existing Internet infrastructure as the underlay network. Another architecture is Detour [11]. It is revealed in [11] that a large percentage of flows can find better alternative routes by relaying among overlay nodes, which improves the performance of those flows.

As the amount of traffic generated by overlay networks increases, the dynamics of overlay routing have significant impacts on VNT control. One typical impact is the selfish behavior of overlay routing as discussed in [12]. Since nodes of overlay networks independently select their route in a selfish manner to optimize their own performance, the system-wide performance may not be optimized [13]. Another impact on VNT control is the high variance in the traffic demand matrix induced by overlay routing. Since origin-destination pairs in overlay networks traverse several source-destination pairs in IP networks, the traffic demand matrix of the IP networks highly depends on the overlay routing. When the VNT is reconfigured in response to changes of traffic demand due to the overlay routing, the network status measured at the overlay network may be changed. This leads to the re-adaptation of the overlay network via overlay routing, which in turn changes in the traffic demand matrix for VNT control. In this way, coexistence of overlay routing and VNT control leads to a high variance of the traffic demand matrix, as we will demonstrate in Section II.

The interaction between overlay routing and packet layer traffic engineering (TE) has been studied in many papers. In the packet layer TE, the routing of IP traffic is controlled to

[1] In the literature, a virtual network topology provided by a set of lightpaths is sometimes called logical topology. In this paper, we use the term "logical topology" in the context of an overlay's logical topology, and use the term "VNT" for virtual network topology provided by the lightpaths.

satisfy its quality requirements. In [12], the authors reveal that the interaction between overlay routing and packet layer TE causes a degradation of the performance of packet layer TE. They argue that the main reason for this degradation is caused by a conflict of two different routing objectives performed at each layer. The impact of selfish routing in intra-domain networks is also investigated in [14]. According to [14], selfish routing can achieve almost optimal performance in the case that an underlay network performs static routing. However, if packet layer TE is used, the performance of the packet layer TE is degraded due to the interaction between overlay routing and packet layer TE. However, these papers show that the performance of the packet layer TE is degraded in terms of maximum link utilization, network cost, and average latency. Since VNT is configured according to the traffic demand matrix, the fluctuation in the traffic demand matrix induced by overlay routing is much more serious for VNT control.

In this paper, we consider a network architecture where an overlay network performs dynamic routing based on its own policy above a VNT. We first show that overlay routing highly degrades the performance of VNT control. Then we focus on the instability of VNT control caused by the interaction between overlay routing and VNT control. Simulation results show that the instability appears in link utilization, traffic demand, and VNTs due to VNT control. To improve the stability of VNT control, we introduce *hysteresis* to absorb the fluctuation of the traffic demand. We show that simple applications of hysteresis can improve the stability, but cannot always improve the performance. We extend the application of hysteresis and show that this extension can improve both the stability and the performance of VNT control.

The rest of this paper is organized as follows. In Section II, we show performance degradations of the underlay network and show that the coexistence of overlay routing and VNT control results in significant instability of the underlay network. We introduce hysteresis in order to overcome the instability in Section III, and show that the simple applications of hysteresis cannot improve the performance. Thus, in Section IV, we extend the application of hysteresis to improve both the stability and the performance, and we finally conclude this paper in Section V.

II. INSTABILITY OF NETWORK STATE

In this section, we investigate the influence of overlay routing on the dynamically configured VNT. Through simulation experiments, we show that the existence of overlay routing services increases the maximum link utilization of the VNT. We also show that the coexistence of overlay routing and VNT control leads to an instability of the VNT.

A. Network Model

In our view, a network consists of three layers: an optical layer, a packet layer, and an overlay layer as shown in Fig. 1. On the optical layer, the WDM network consists of OXCs and optical fibers. Lightpaths are configured between IP routers via OXCs on the WDM network and these lightpaths and IP routers form a VNT. The WDM network provides the VNT to the packet layer and packets are forwarded on the VNT. On the overlay layer, overlay nodes built upon the packet layer form an overlay network.

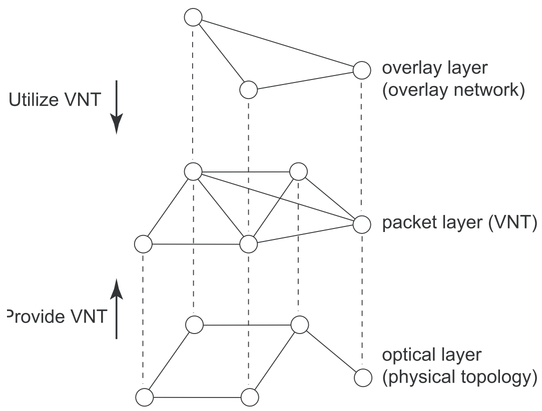


Fig. 1. An example of a network consists of three layers; optical, packet, and overlay layers.

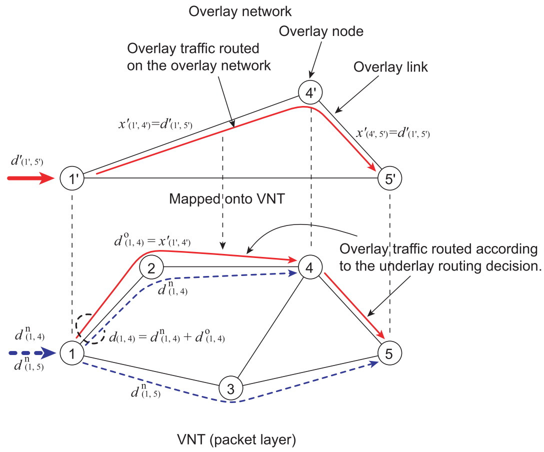


Fig. 2. An illustrative example of VNT and overlay.

In this network, two types of traffic are carried over the VNT: the traffic from overlay networks and the traffic from non-overlay networks. We refer to *overlay traffic* as the traffic in the overlay network and *non-overlay traffic* in the non-overlay network. We also use the term *underlay traffic* for all traffic on the VNT, which contains overlay traffic and non-overlay traffic.

A route r for forwarding the underlay traffic on the VNT is expressed as a sequence of L_v, where L_v is a set of links on the VNT. We represent a routing matrix on the VNT by a $m \times q$ matrix A, where m is the number of links on the VNT, and q is the number of source-destination pairs. An entry in this matrix $A(l, p)$ is set to 1 if the underlay traffic between a source-destination pair p is routed over a link l. Otherwise, $A(l, p)$ is set to 0. The traffic demand of the network is expressed as a q dimensional vector $D = \{d_p\}$, where d_p is the traffic demand for the source-destination pair p. Then, the total amount of traffic x_l that goes through a link l is derived from $x_l = \sum_i A(l, i) \cdot d_i$.

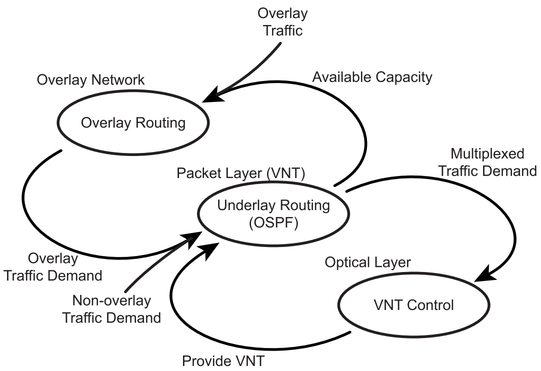


Fig. 3. The interaction between VNT control and overlay routing.

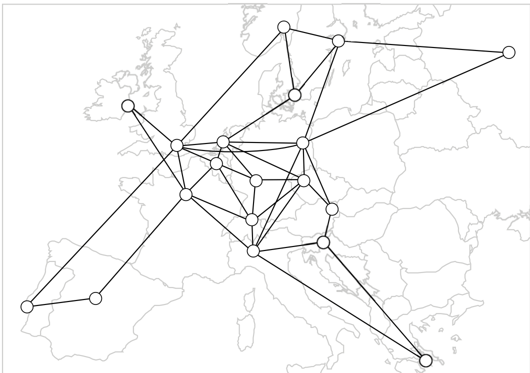


Fig. 4. European Optical Network (EON) topology.

The vector $X = \{x_l\}$ is defined as $X = AD$.

The overlay network forms a logical topology on top of the VNT and makes its routing decision on that logical topology. The routing matrix, the traffic volume on each overlay link, and the traffic demand on the overlay network is defined in a similar way to those on the VNT. That is, the routing matrix of the overlay network, B, is represented as a $m' \times q'$ matrix, where m' is the number of links on the logical topology of the overlay network, and q' is the number of the overlay's source-destination pairs. The traffic volume on an overlay link l' is $x'_{l'}$ and the vector $X' = \{x'_{l'}\}$ is defined as $X' = BD'$, where D' is the traffic demand vector on the overlay network.

In the following, we explain how an overlay traffic is forwarded on the VNT. We represent an overlay node built upon the underlay node i on the VNT as i'. The overlay node i' is connected to an other overlay node j' by a logical link $l' = (i', j')$. The overlay traffic on l' (denoted as $x'_{l'}$) is forwarded from i to j according to the routing matrix A. The traffic demand on the VNT due to the overlay network is expressed as $d^{\mathrm{o}}_{(i,j)} = x'_{l'}$. Here, we define the traffic demand due to non-overlay traffic as D^{n}. The traffic demand of the underlay traffic D is given by the sum of overlay and non-overlay traffic $D = D^{\mathrm{n}} + D^{\mathrm{o}}$. Note that the traffic demand between a source-destination pair varies according to $d^{\mathrm{o}}_{(i,j)}$. We illustrate an example of these mapping relations between the VNT and the overlay in Fig. 2. The VNT that has five nodes and six lightpaths is configured. The overlay nodes $1'$, $4'$, and $5'$, which are built upon the underlay nodes 1, 4, and 5, respectively, form the overlay network on the VNT. In this example, the traffic demand on the overlay network $d'_{(1',5')}$ and the traffic demand due to the non-overlay traffic $d^{\mathrm{n}}_{(1,4)}$ are considered. The traffic demand $d'_{(1',5')}$ is forwarded via node $4'$, and $x'_{(1',4')}$ and $x'_{(1',5')}$ are $d'_{(1',5')}$. On the VNT, $d'_{(1',5')}$ is first forwarded from node 1 to 4 via 2 and from node 4 to 5 according to the routing decision on the VNT. The traffic demand due to the overlay traffic $d^{\mathrm{o}}_{(1',4')}$ is equivalent to $x'_{(1',4')}$, and so the traffic demand from node 1 to 4 is expressed as $d_{(1,4)} = d^{\mathrm{o}}_{(1',4')} + d^{\mathrm{n}}_{(1,4)}$.

B. Simulation Model

A model for evaluating an interaction between overlay routing and packet layer TE is introduced in [12]. The model consists of an overlay layer and a packet layer. In this paper, we introduce an optical layer into that model and evaluate the interaction between overlay routing and VNT control through the packet layer. Fig. 3 illustrates our model.

1) Overlay routing: Several routing policies for overlay networks such as selfish overlay routing and optimal overlay routing are proposed and evaluated in many papers [14]–[16]. Among them, we use selfish overlay routing where each overlay node selects the route that has the largest available bandwidth. This route selection is done in a selfish manner aiming at maximizing the throughput experienced by the overlay nodes. The available bandwidth a_l on link l is calculated as $a_l = c_l - x_l$, where c_l is the capacity of link l, and that along route r is represented by $a(r) = \min_{l \in r}(a_l)$. The overlay network selects the route r that satisfies $a(r) = \max_{i \in R} a(i)$, where R denotes the set of all possible routes.

Several papers propose to improve the performance of the overlay network by relaxing the selfishness or greediness of overlay routing [15], [16]. However, we do not assume that overlay networks employ these cooperative approaches since our intention is to obtain a robust VNT control method against selfish and greedy overlay networks.

2) VNT control: The VNT is configured according to its performance objective by the VNT control method. Several performance objectives for selecting VNTs are studied in [17]–[19], minimizing average weighted number of hops, minimizing congestion, maximizing single hop traffic, and minimizing average delay. Many VNT control algorithms for achieving those performance objectives are studied [9], [20]–[22]. Since congestion directly affects the available bandwidth, which the overlay network seeks to optimize, we employ algorithms for minimizing congestion to investigate the interaction between overlay routing and VNT control. Note that congestion is the total amount of traffic on links. For minimizing congestion, MLDA (Minimum delay Logical topology Design Algorithm) [9] and e-MLDA (extended MLDA) [20] are studied. MLDA aims at minimizing average delay as its performance objective by solving the RWA problem, but the main objective for configuring VNTs is to minimize congestion. e-MLDA is proposed as an extension of MLDA to ensure the accommodation of the traffic demand. e-MLDA also tries to decrease congestion in the network by taking into account the minimum hop IP routing. All these algorithms configure VNTs according to traffic demand to optimize their performance objectives. Note that VNT control cannot distinguish between D^{n} and D^{o}. That is, it uses only combined traffic demand D.

3) Interaction between overlay routing and VNT control: When the overlay network switches its routes, the traffic demand D^{o} changes. As response to this traffic change, VNT control reconfigures its VNT. This reconfiguration updates the available bandwidth. The overlay network again switches to the new route that is superior to the previous route to improve the throughput of the overlay traffic. In our simulation experiments, each layer takes the above-mentioned actions and updates their status alternately. More specifically, overlay routing makes decisions at odd rounds and VNT control reconfigures its topology at even rounds. We use OSPF routing protocol for the routing in the packet layer. Since our main purpose is to investigate the interaction between overlay routing and VNT control, shortest hop paths are used for forwarding traffic on the packet layer, that is, all weights are set to 1.

We evaluate this interaction with the maximum link utilization, which is the total amount of traffic on a link divided by its capacity since the main objective of MLDA and e-MLDA is to minimize congestion. We note that links are overloaded if the utilization exceeds 1, and in this case, no bandwidth is available at these links. We set the capacity of a lightpath to 1, that is, the link capacity is equivalent to the number of lightpaths, and all traffic used in our evaluation is normalized by the capacity of a lightpath.

In our simulation, the overlay network constructs a fully connected topology in the same way as the environments in [10], [14]. We also place overlay nodes on all underlay nodes. Each overlay node independently searches for the route with the largest available bandwidth in a selfish manner. We assign a proportion of d_{ij} as overlay traffic, and the rest as non-overlay traffic, that is, the traffic demand of overlay traffic is $\alpha \cdot d_{ij}$, and that of non-overlay traffic is $(1-\alpha) \cdot d_{ij}$.

4) Simulation parameters: We use the European Optical Network (EON) topology with 19 nodes and 39 bidirectional links (Fig. 4) for the physical topology. To simplify the interaction model, we do not take into account the wavelength continuity constraint in these experiments, that is, we assume that all nodes have full wavelength converters on all input and output ports and each node has 8 ports for each direction (i.e., 8 input ports and 8 output ports). We use a randomly generated traffic demand vector in the following evaluations.

C. Degradation of Underlay Network Performance

The main purpose of this subsection is to investigate the influence that overlay routing has on VNT control. For the purposes of comparison, we use fiber topologies, where lightpaths are statically configured on a single fiber, i.e., the VNT is equivalent to the physical topology, and the configured topology is fixed.

We show the maximum link utilization in Fig. 5. In this figure, the horizontal axis shows the total amount of traffic demand and the vertical axis shows the maximum link utilization. We observe that the maximum link utilization increases as the proportion of the overlay traffic increases in the case of all the VNT control algorithms. With a small amount of overlay traffic ($\alpha = 0.1$), the maximum link utilization of MLDA and e-MLDA with overlay traffic is twice as large as the result without overlay traffic, and a slight degradation is observed in the case of the fiber topology. Although the utilization of the fiber topology gets larger as α increases, the utilization of MLDA and e-MLDA increases much more severely compared to the result of the fiber topology. Two factors can be considered for this degradation. One is due to the interaction between overlay nodes, and another is due to the interaction between VNT control and overlay routing. We refer to the interaction between VNT control and overlay routing as the *vertical interaction* and the interaction between overlay nodes as the *horizontal interaction*. Note that only the horizontal interaction appears in the fiber topology since no VNT reconfiguration is made for the fiber topology. In the case of MLDA and e-MLDA, both the vertical interaction and the horizontal interaction degrade the maximum link utilization since a VNT is reconfigured in response to the dynamics of overlay routing. By comparing the results of MLDA or e-MLDA with the results of the fiber topology, we can see that the horizontal interaction does not affect the maximum link utilization and the vertical interaction increases the maximum link utilization greatly.

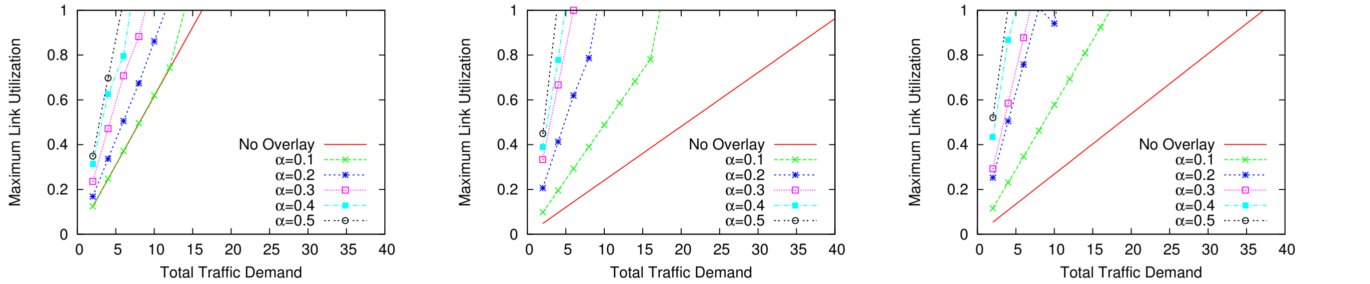
D. Instability due to Coexistence of Two Routing Mechanisms

In the previous section, we showed that the vertical interaction between overlay routing and VNT control degraded the maximum link utilization. In this section, we show that the coexistence of both overlay routing and VNT control leads to instability of VNT control.

Fig. 6 shows that the maximum link utilization depends on the rounds at which VNT control or overlay routing take their actions. In this figure we set α to 0.2. When a VNT is dynamically controlled (i.e., MLDA or e-MLDA is applied), the fluctuation of the maximum link utilization is larger and the cycle of the fluctuation is irregular. That is, the network becomes unstable due to the vertical interaction.

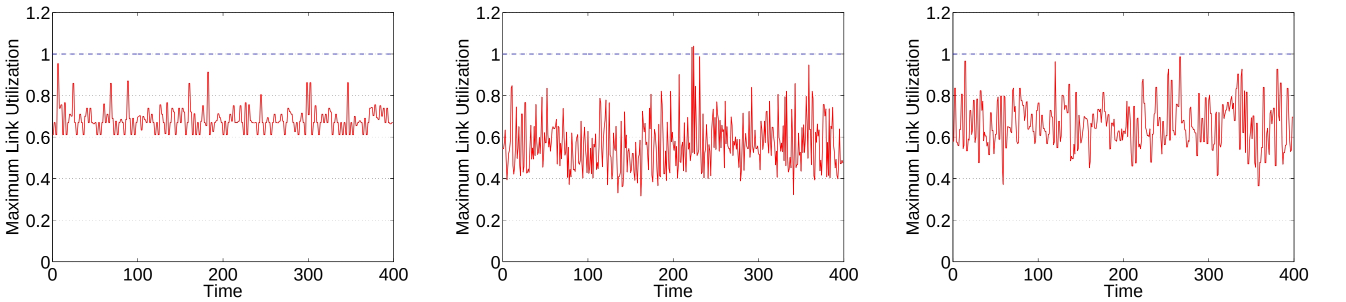
Fig. 7 shows the fluctuation of the traffic volume on each link. The error bars show the maximum and minimum values of the traffic volume in the evaluation, and a point in the bar indicates the average value during the simulation. The horizontal axis represents the link index that is specified uniquely by the source-destination pair. On the fiber topology, the traffic volume fluctuates only for some of the links. However, in the case of MLDA and e-MLDA, the traffic volume of almost all links fluctuates.

The vertical influence is also significant in the traffic demands for source-destination pairs on the VNT. Fig. 8 shows the maximum, minimum, and average of traffic demand for each node pair. It is also observed that the traffic demand



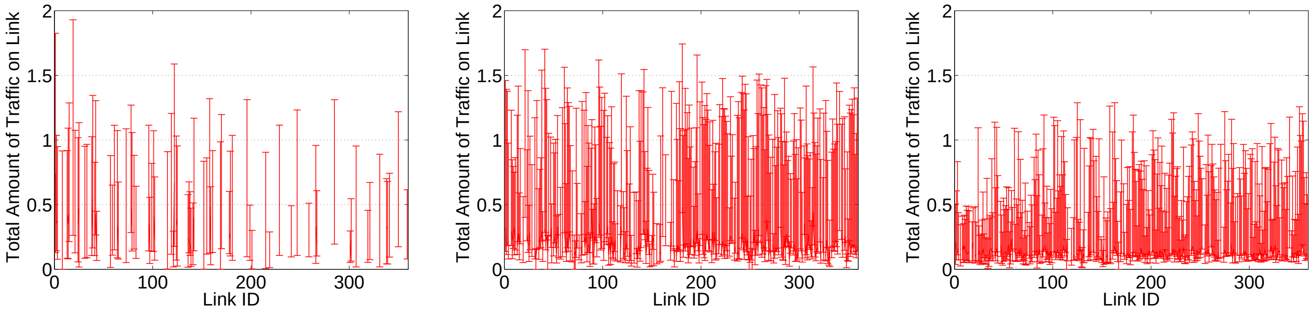
(a) Fiber topology (b) MLDA (c) e-MLDA

Fig. 5. Maximum link utilization (Number of ports: 8).



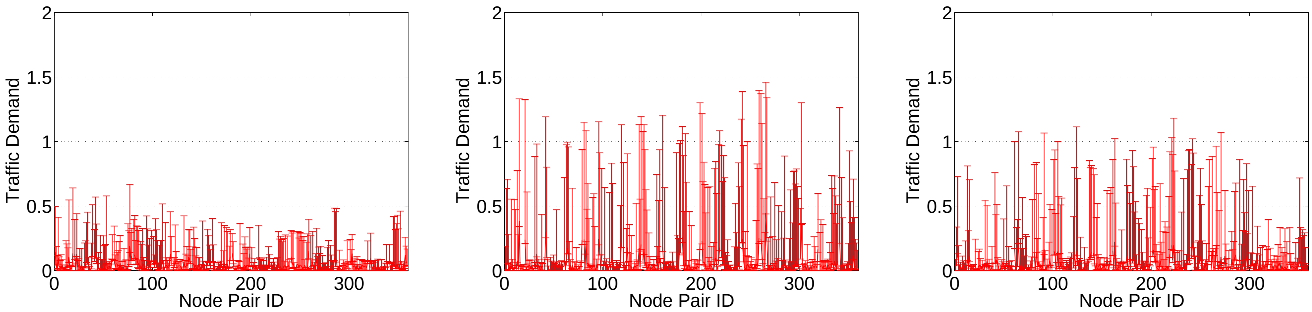
(a) Fiber topology (b) MLDA (c) e-MLDA

Fig. 6. Fluctuation of maximum link utilization (EON, α = 0.2, Total traffic: 10, Number of ports: 8).



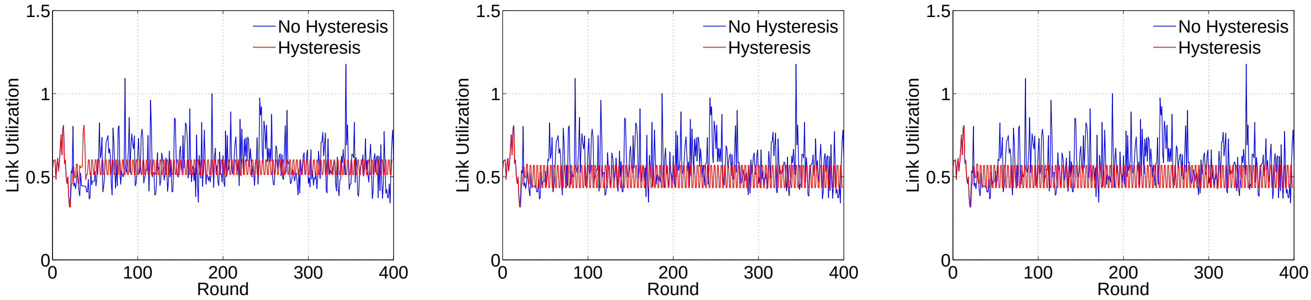
(a) Fiber topology (b) MLDA (c) e-MLDA

Fig. 7. Traffic volume on each link (EON, α = 0.2, Total traffic: 10, Number of ports: 8).



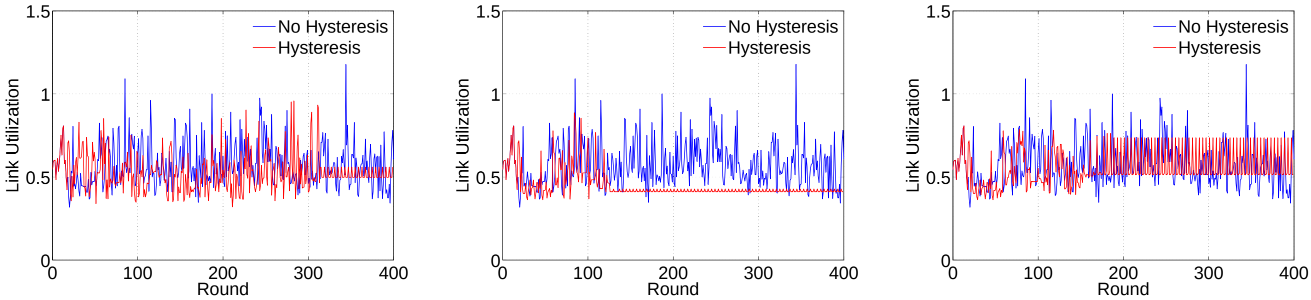
(a) Fiber topology (b) MLDA (c) e-MLDA

Fig. 8. Fluctuation of traffic demand (EON, α = 0.2, Total traffic: 10, Number of ports: 8).



(a) $H = 0.0$ (b) $H = 0.2$ (c) $H = 0.4$

Fig. 9. Fluctuation of maximum link utilization (Utilization hysteresis, $\alpha = 0.2$, Total traffic: 10, Number of ports: 8).



(a) $H_u = 0.1$ (b) $H_u = 0.3$ (c) $H_u = 0.5$

Fig. 10. Fluctuation of maximum link utilization (Demand hysteresis, $\alpha = 0.2$, Total traffic: 10, Number of ports: 8).

fluctuates drastically when the VNT is dynamically controlled via MLDA or e-MLDA. If overlay routing and VNT control coexist on the same network, the network state becomes unstable and its performance is degraded drastically. The main reason for this instability is that the existing VNT control algorithms generate VNTs according to the current traffic demand. As shown in Fig. 8, if there is selfish overlay routing in the network, the traffic demand changes extremely. Since the traffic demand is the most important input parameter for designing VNTs, the fluctuation of the traffic demand leads to a significant instability of VNT control.

III. IMPROVEMENTS IN STABILITY OF NETWORK STATE

A. Application of Hysteresis

In this section, we apply *hysteresis* to VNT control in order to overcome the problem of the vertical interaction. Hysteresis is the property of systems that do not immediately react to forces applied to them. This property is often used to avoid routing fluctuation [10], [16], [23].

As presented in the previous section, the traffic demand heavily fluctuates in the case that overlay routing and VNT control coexist. Because the traffic demand is the input parameter of the VNT control algorithms, one possibility is to apply hysteresis to the traffic demand in order to suppress the influence imposed by overlay routing. We refer to this application as *demand hysteresis*. Another application is *utilization hysteresis* where the hysteresis property is used for the maximum link utilization. In the case of utilization hysteresis, the current VNT is kept if the improvement in the link utilization of the new VNT is less than a certain hysteresis threshold. We expect that this results in a decrease in the number of VNT reconfiguration. We describe each application more specifically in the following sections.

1) Demand hysteresis: Demand hysteresis works as follows. Let $D(t) = \{d_p(t)\}$ denote the traffic demand for node pair p at the round t and $D(t-2)$ denote the previously observed traffic demand at round $t-2$. Note that the overlay network updates its routing matrix at round $t-1$. We first temporarily calculate a VNT $C^h(t)$ using the current traffic demand $D(t)$. The VNT $C^h(t)$ is represented by a set of $c_p^h(t)$, where $c_p^h(t)$ is the capacity between node pair p at round t. We then compare the traffic demand $d_p(t)$ with $d_p(t-2)$ for each node pair. If the current traffic demand $d_p(t)$ decreases below the ratio of H_l or increases above the ratio of H_u, we use $c_p^h(t)$ as the new capacity for node pair p. Otherwise, $c_p(t-2)$ is kept. More precisely, $c_p(t)$ is updated by the following equations.

$$c_p(t) = \begin{cases} c_p^h(t) & \text{if } d_p(t) > (1 + H_u) \cdot d_p(t) \\ c_p^h(t) & \text{if } d_p(t) < (1 - H_l) \cdot d_p(t) \\ c_p(t-2) & \text{otherwise} \end{cases}$$

Demand hysteresis is aimed at stabilizing VNT control by absorbing the fluctuation of the traffic demand, which reduces unnecessary topology changes. That is, VNT control to which demand hysteresis is applied reacts slowly against the heavy fluctuation of the traffic demand. However, since the main objective of demand hysteresis is not an improvement in maximum link utilization, the resulting VNT may not show a good performance in terms of maximum utilization.

2) Utilization hysteresis: Utilization hysteresis works as follows. Similar to demand hysteresis, we first temporarily calculate the VNT, $C^h(t)$, using the current traffic demand $D(t)$. We then calculate the expected link utilization $U^h(t)$ using $D(t)$ and $C^h(t)$. We next compare the maximum link utilization $\max(U^h(t))$ with $\max(U(t-1))$, where $U(t-1)$ is the link utilization after the overlay network updates its route. If the improvement in the maximum link utilization is larger than the ratio of H, we use $C^h(t)$ as the new VNT. Utilization hysteresis is formulated as follows,

$$C(t) = \begin{cases} C^h(t) & \text{if } \max(U^h(t)) < (1-H)\cdot\max(U(t-1)) \\ C(t-2) & \text{otherwise} \end{cases}.$$

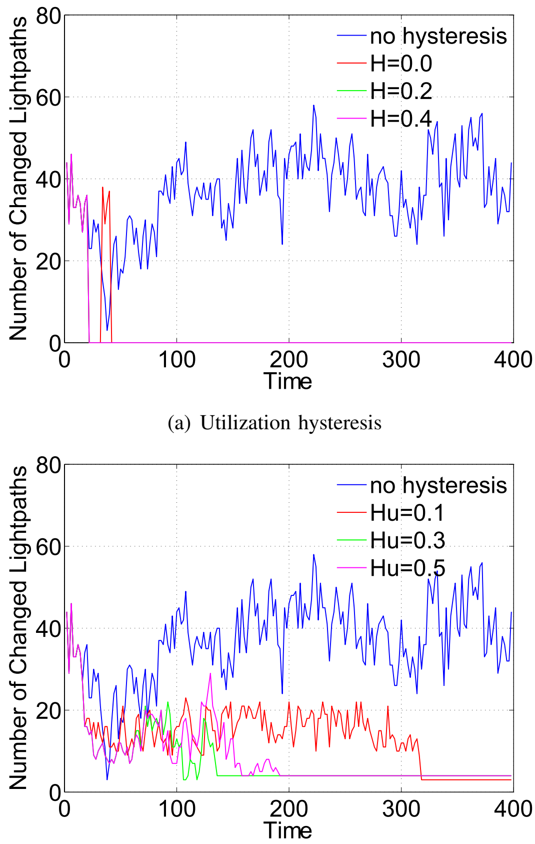
Utilization hysteresis stabilizes VNT control by keeping the current VNT if the benefit of changing to the new VNT is small.

B. Performance Evaluation

We evaluate demand hysteresis and utilization hysteresis via computer simulations. We use the same simulation model as presented in Section II, but in this section, MLDA is selected as the VNT control algorithm. In obtaining the following figures, the hysteresis mechanisms are not applied during the first 20 rounds to ignore the transient phase. Figs. 9 and 10 show the fluctuation of the maximum link utilization when utilization hysteresis and demand hysteresis are applied. The vertical axis shows the maximum link utilization and the horizontal axis shows the rounds. Looking at these figures, we observe that the maximum utilization with utilization hysteresis is stable compared to the results without hysteresis.

However, in contrast to utilization hysteresis, the maximum utilization still fluctuates for demand hysteresis. The main purpose of demand hysteresis is to decrease the number of changed lightpaths by absorbing the fluctuation of the traffic demand due to overlay routing. However, decreasing the number of changed lightpaths cannot lead to an improvement in the stability of the maximum link utilization. To explain this more clearly, we evaluate two hysteresis applications in Fig. 11 by comparing the number of changed lightpaths to investigate the efficiency of demand hysteresis. Here, we define the number of changed lightpaths at round t as $\sum |c_e(t)-c_e(t-2)|$. The number of changed lightpaths is decreased by more than 50% in the case that demand hysteresis is applied. However, demand hysteresis cannot make the number of changed lightpaths become 0 since traffic demand still fluctuates due to the selfish behavior of overlay routing. In the case of utilization hysteresis, the number of changed lightpaths is always zero if VNT control maintains the current VNT.

More detailed observations of these figures indicate that the performance does not strongly depend on the decision of the hysteresis threshold H in the case that utilization hysteresis is applied. If a large hysteresis threshold H is used, the VNT control does not immediately react against the changes in the network environments. This means that a large H leads to a worse performance since the VNT configured for the previously observed traffic demand is kept. However, the result in Fig. 9 is different from the expected result. We change the ratio of overlay traffic α from 0.2 to 0.3 in Figs. 12 and 13. In Fig. 12, the maximum link utilization of $H = 0.0$ is the lowest, while the utilization of $H = 0.0$ in Fig. 9 is the highest. Moreover, the average maximum link utilization with hysteresis is worse than that without hysteresis. These results indicate that the network performance does not strongly depend on the hysteresis threshold H itself. The VNT control method with demand hysteresis in Fig. 13 ($\alpha = 0.3$) does not lead to a stable state. Since demand hysteresis is not effective compared to utilization hysteresis, in the next section, we will focus on utilization hysteresis and extend it to avoid slipping into undesirable stable states.



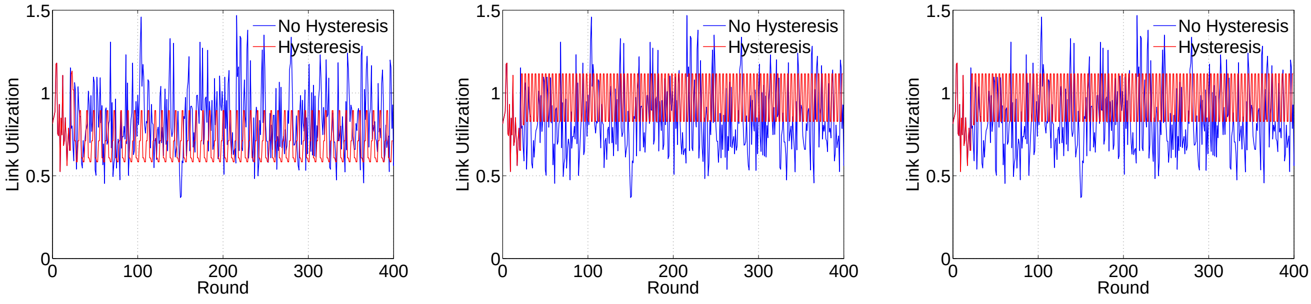
(a) Utilization hysteresis

(b) Demand hysteresis

Fig. 11. Number of changed lightpaths (EON, $\alpha = 0.2$, Total traffic: 10, Number of ports: 8).

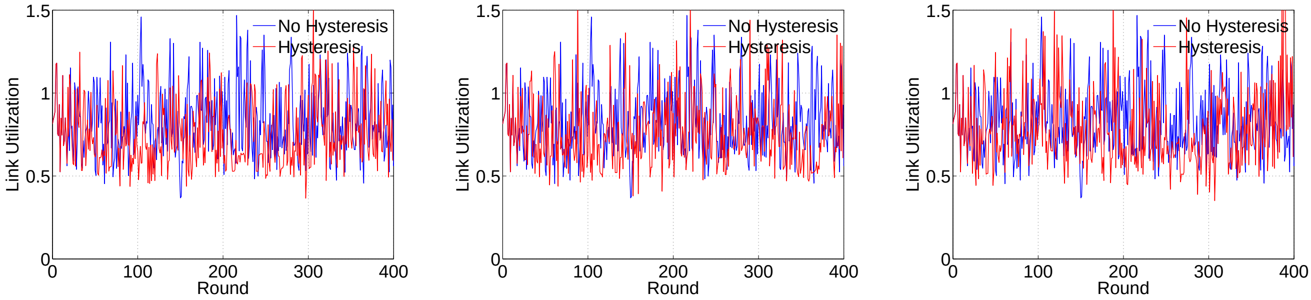
IV. PROPOSED METHOD

Applying utilization hysteresis to VNT control can improve the stability of the network, but cannot always improve the performance as shown in the previous section. In this section, we extend utilization hysteresis to improve both the stability and the performance.



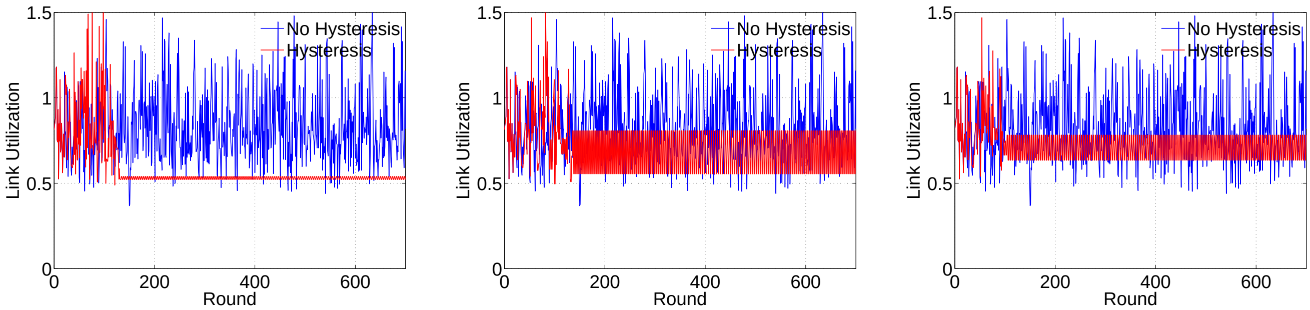
(a) $H = 0.0$ (b) $H = 0.2$ (c) $H = 0.4$

Fig. 12. Fluctuation of maximum link utilization (Utilization hysteresis, $\alpha = 0.3$, Total traffic: 10, Number of ports: 8).



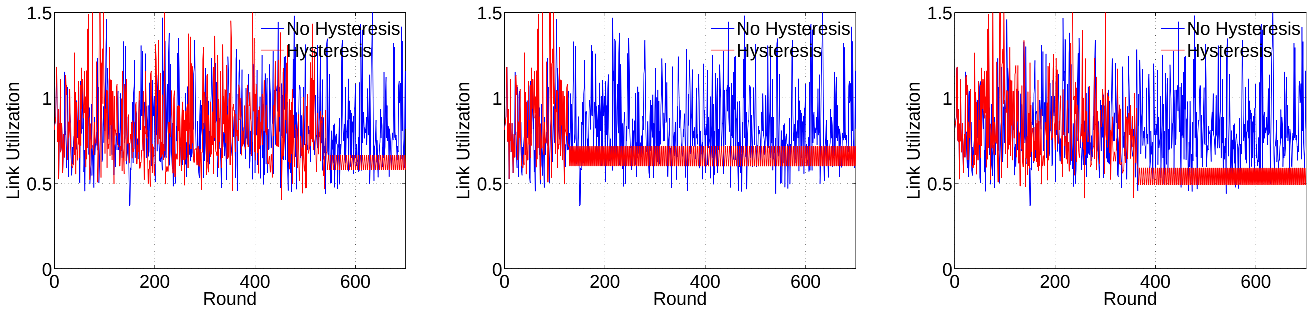
(a) $H_u = 0.1$ (b) $H_u = 0.3$ (c) $H_u = 0.5$

Fig. 13. Fluctuation of maximum link utilization (Demand hysteresis, $\alpha = 0.3$, Total traffic: 10, Number of ports: 8).



(a) $H = 0.0$ (b) $H = 0.2$ (c) $H = 0.4$

Fig. 14. Fluctuation of maximum link utilization ($\alpha = 0.3$, Total traffic: 10, Number of ports: 8, $k = 3.0$).



(a) $H = 0.0$ (b) $H = 0.2$ (c) $H = 0.4$

Fig. 15. Fluctuation of maximum link utilization ($\alpha = 0.3$, Total traffic: 10, Number of ports: 8, $k = 5.0$).

A. Two State Utilization Hysteresis

As we discussed in Section III-B, utilization hysteresis can improve the network stability, but cannot always converge to a state that shows lower maximum link utilization. The reason is that the VNT control method with utilization hysteresis slips into a stable state when it decides to keep using the current VNT for two consecutive rounds of VNT control. Therefore, we extend utilization hysteresis named *two state utilization hysteresis* to prevent VNT control from slipping into a stable state when the maximum link utilization is high. For this purpose, we introduce another threshold θ that controls whether utilization hysteresis is applied or not. If the current maximum link utilization u is higher than θ, utilization hysteresis is not applied to VNT control to avoid slipping into an undesirable state. Otherwise, utilization hysteresis described in Section III is performed. We define the threshold $\theta = u_l + (u_u - u_l)/k$ where u_l and u_u are the minimum and maximum value of the maximum link utilization obtained so far, respectively, and k is a control parameter for adjusting θ. The utilizations u_l and u_u are updated every time when VNT control is performed, and therefore no history of the utilization is required. When u is higher than θ, VNT control regards that the maximum link utilization of the current VNT is high. In this case, utilization hysteresis is not applied to VNT control, and the VNT is immediately reconfigured to avoid slipping into a stable state that has a high maximum link utilization. Then VNT control again searches another stable state where the maximum link utilization is sufficiently low.

B. Performance Evaluation

We evaluate two state utilization hysteresis under the same simulation model as the previous section. The simulation parameters are set to the same ones as in Fig. 12. Figs. 14 and 15 show the fluctuation of the maximum link utilization in the case that k is 3.0 and 5.0, respectively. These figures clearly indicate that VNT control gets stable and the maximum link utilization is lower than that in Fig. 12. However, these figures also exhibit that the convergence time, which is defined as the time until the VNT gets stable, becomes longer than that in Fig. 12. This is because that a larger value of k more restricts the region where utilization hysteresis is applied, and thus it is more difficult to seek the stable state that has lower maximum link utilization.

In this section, we evaluated two state utilization hysteresis. VNT control with two state utilization hysteresis can make the VNT stable and improve the maximum link utilization. However, with a large α, the degradation of the performance is serious, as we have discussed in Section II. In these highly loaded environments, operating the VNT at a stable state is more important than improving the performance via VNT control. In this sense, conservative settings of parameter k may be appropriate for VNT control. An adaptive setting of k will make VNT control more robust and efficient, but its algorithm is one topic of our future research.

V. CONCLUSION

In this paper, we investigated the selfish behavior of overlay routing above a VNT. We revealed that the dynamics of overlay routing causes high fluctuations in traffic demand, which leads to a significant instability of VNT control. To overcome the fluctuation of the traffic demand and to make VNT control more stable, we applied demand hysteresis and utilization hysteresis to VNT control. We found that demand hysteresis could improve the stability in terms of the number of changed lightpaths, but could not provide a stable maximum link utilization, especially when the ratio of the overlay traffic is large. We also found that utilization hysteresis could improve the stability, but could not always improve the maximum link utilization. We therefore proposed a two state hysteresis method that applies utilization hysteresis only when the maximum link utilization is sufficiently low. Simulation results indicated that two state hysteresis improves both the stability and the maximum link utilization. However, the convergence time becomes longer.

As future work, we intend to investigate further VNT control algorithms, other than MLDA, that provide more stable VNTs for overlay routing.

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