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オーバーレイネットワークの安定収容のためのVNT制御手法

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あらまし　アプリケーションレベルで経路制御（オーバーレイルーティング）を行うことで、サービスが必要とする品質を IP 網上から引き出すオーバーレイネットワークが注目されている。しかし、オーバーレイルーティングとトラヒックエンジニアリングが同一ネットワークに存在すると、互いの経路制御が競合しネットワークの性能および安定性が劣化することが指摘されている。本稿では WDM 技術を用いたトラヒックエンジニアリングである VNT (Virtual Network Topology) 制御とオーバーレイルーティングに着目し、VNT 制御の安定性と性能を向上するための手法を提案する。シミュレーションにより提案手法が VNT 制御の安定性と性能を向上させることを明らかにする。

キーワード　波長分割多重、仮想網制御、オーバーレイルーティング、安定性、ヒステリシス

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

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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 cause a high fluctuation in the traffic demand, which leads to significant instability of VNT control. To overcome the instability induced by the overlay routing, we introduce three extensions, *utilization hysteresis*, *two-state utilization hysteresis*, and *filtering*, to VNT control. Through simulations, we show that our methods achieve the stability against overlay routing without the loss of the adaptability for changes in the traffic demand.

Key words　Wavelength Division Multiplexing, VNT Control, Overlay Routing, Stability, Hysteresis

1 Introduction

Wavelength Division Multiplexing (WDM) technology, which carries multiple wavelength channels on a single fiber, is expected to accommodate 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 [1–5]. One approach to accommodate IP traffic on a WDM network is to establish 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 VNTs based on the traffic demand, has been studied [6, 7].

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 [8, 9]. The fundamental idea of overlay routing is to construct a logical network above the IP network and to allow routing to be controlled on that logical topology. 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. Each overlay node measures status, such as throughput and delay, of the underlying network, and determines the appropriate route on the overlay network to improve the performance. The resilient overlay network (RON) architecture is proposed in [8]. 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 [9]. In [9], it is revealed 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 [10]. Since overlay nodes independently select their route in a selfish manner to optimize their own performance, the system-wide performance may not be optimized. Another impact on VNT control is the heavy fluctuation in the traffic demand induced by overlay routing. Since origin-destination pairs in overlay networks traverse several source-destination pairs in IP networks, the traffic demand of the IP networks strongly depends on the overlay routing. When the VNT is reconfigured in response to changes in the 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 for VNT control. In this way, the coexistence of overlay routing and VNT control leads to a heavy fluctuation in the traffic demand.

The interaction between overlay routing and packet layer traffic engineering (TE) has been studied in many papers [11, 12]. In the packet layer TE, the routing of IP traffic is controlled to satisfy its quality requirements. In [12], it is revealed that the interaction between overlay routing and packet layer TE degrades the performance of 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, the fluctuation in the traffic demand induced by overlay routing is much more serious for VNT control.

In this paper, we consider a network 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 show the instability due to the interaction appears in link utilization and traffic demand. To overcome this instability and achieve a stable VNT control method against overlay routing, we propose three extensions for VNT control. First, to improve the stability of VNT control, we introduce *utilization hysteresis*. We show that utilization hysteresis improves the stability, but does not always improve the performance. We extend utilization hysteresis, *two-state utilization hysteresis*, and show that this improves both the stability and the performance of VNT control. However, two-state utilization hysteresis requires a long time until VNT control becomes stable. Thus, we achieve the fast convergence by adopting a *filtering* method, which reduces small changes in VNTs. Finally, we show that our methods follow changes in the traffic demand, and therefore we achieve stable VNT control against overlay routing.

The rest of this paper is organized as follows. In Section 2, we show that overlay routing degrades performance of the underlay network and the coexistence of overlay routing and VNT control results in significant instability of the underlay network. We introduce utilization hysteresis to overcome the instability in Section 3, and show that this does not always improve the performance. Thus, in Section 4, we extend utilization hysteresis. Although two-state utilization hysteresis improves both the stability and the performance, it takes long time until VNT control gets stable. Therefore, we introduce a filtering method and achieve the fast convergence in Section 5. In Section 6, we show the adaptability of our methods for the changes in the traffic demand, and we finally conclude this paper in Section 7.

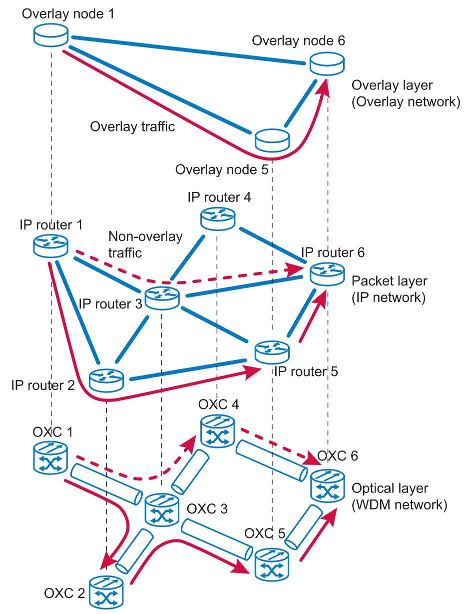


Fig. 1 An example of a network consists of three layers; optical, packet, and overlay layers.

2 Instability of Network State

In this section, we investigate the influence of overlay routing on the dynamically configured VNT.

2.1 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 fibers. VNT control configures lightpaths between IP routers via OXCs and these lightpaths and IP routers form a VNT. On the packet layer, packets are forwarded along the routes that are decided by IP routing on this VNT. On the overlay layer, overlay nodes built on the packet layer form an overlay network. In this network, two types of traffic are carried over the VNT: the traffic from overlay networks and the traffic from non-overlay networks, which are illustrated as solid and dashed arrows in Fig. 1, respectively. We refer to *overlay traffic* as the traffic in the overlay network and to *non-overlay traffic* as the 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. In Fig. 1, a VNT that has six IP routers and nine links is configured. On this VNT, three overlay nodes form an overlay network. Solid arrows show overlay traffic from the overlay node 1 to 6 and dashed arrows show non-overlay traffic from the IP router 1 to 6. The overlay traffic in this figure is forwarded from the overlay node 1 to 6 by relaying through the overlay node 5. Overlay links are transport tunnels over the IP network in the sense that the traffic on the overlay links is forwarded on the IP network and its route on the IP network is decided by IP routing. Thus, the traffic on the overlay link between the overlay node 1 and 5 is forwarded along the route decided by IP routing, that is, from the IP router 1 to 5 through the IP router 2. Then, the overlay traffic is forwarded from the overlay node 5 to 6 in the same way. In this case, the traffic demand from the overlay node 1 to 6 is recognized as the two separated traffic demand, which are the traffic demand from IP router 1 to 5 and 5 to 6, by IP network or VNT control. Therefore, overlay routing causes the changes in the traffic demand. The non-overlay traffic is forwarded from the IP router 1 to 6 through the router 3, which is also controlled by IP routing. In this paper, we investigate an interaction between overlay routing and VNT control through the IP layer. Before we introduce this interaction, we describe overlay routing and VNT control more precisely.

2.2 Overlay routing

Several routing policies for overlay networks such as overlay selfish routing and overlay optimal routing are proposed and evaluated in many papers [11, 13, 14]. Among them, we use overlay selfish routing where each overlay node selects the route that has the largest available bandwidth. The available bandwidth a_l on link l is $a_l = c_l - x_l$, where c_l is the capacity of l. The available bandwidth 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 [14]. Moreover, the overlay selfish routing of which the routing metric is the available bandwidth is one of the greediest overlay routing services as reported in [14]. In this paper, since our objective is to obtain a robust VNT control method against selfish and greedy overlay networks, we use the overlay network that selects the route with the most available bandwidth and do not assume that it employ those cooperative approaches.

2.3 VNT control

The VNT is configured according to its performance objective by the VNT control method. Many VNT control algorithms for achieving their performance objectives, such as minimizing average weighted number of hops, minimizing maximum link utilization, maximizing single hop traffic, and minimizing average delay, are studied [6, 7, 15, 16]. Since the link utilization directly affects the available bandwidth, which the overlay network seeks to optimize, we employ algorithms for minimizing the maximizing link utilization to investigate the interaction between VNT control and overlay routing. For minimizing the maximum link utilization, MLDA (Minimum delay Logical topology Design Algorithm) [7] is 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 the maximum link utilization. MLDA configures a VNT according to traffic demand to optimize its performance objective. Note that VNT control does note distinguish between the traffic demand due to the overlay traffic and the non-overlay traffic.

2.4 Interaction between overlay routing and VNT control

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. 2 illustrates our model. When the overlay network switches its routes, the traffic demand in the packet layer is changed. To response to this traffic change, VNT control reconfigures its VNT. This reconfiguration changes the available bandwidth. The overlay network again switches to the new route that is superior to the previous route. In our simulation experiments, each layer takes the above-mentioned actions alternately. More specifically, overlay routing makes its decisions at odd rounds and VNT control reconfigures its topology at even rounds. Since our main purpose is to investigate the interaction between overlay routing and VNT control, minimum hop routing is used in the packet layer.

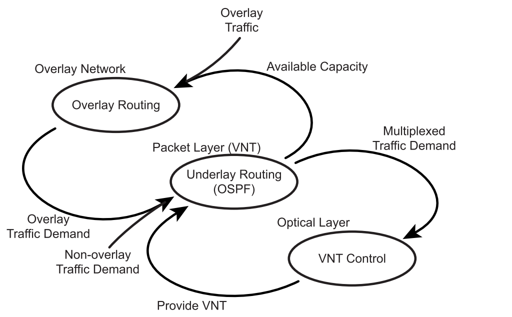


Fig. 2 The interaction between VNT control and overlay routing.

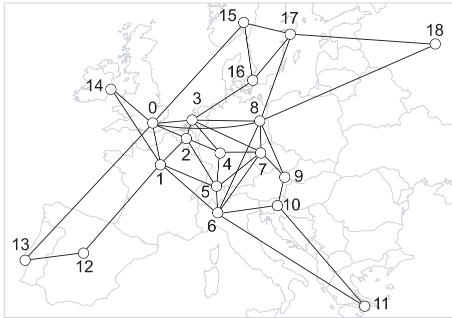


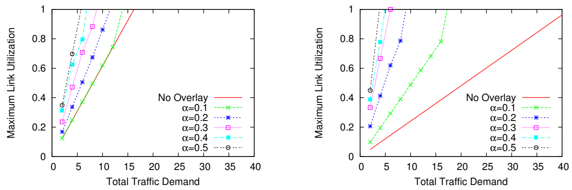
Fig. 3 European Optical Network (EON) topology.

2.5 Simulation model

We evaluate the interaction described above with the maximum link utilization, which is the total amount of traffic on a link divided by its capacity. Note that a link is overloaded if the utilization exceeds 1, and in this case, no bandwidth is available at this link. We set the capacity of one lightpath to 1 and all traffic used in our evaluation is normalized by the capacity of a lightpath. An overlay network constructs a fully connected topology in the same way as the environments in [8, 11]. We place overlay nodes on all IP routers. Each overlay node independently selects routes with the largest available bandwidth. We assign a proportion of the underlay traffic demand, D, as overlay traffic demand, D_o, and the rest as non-overlay traffic demand, D_n, that is, the traffic demand of overlay traffic is $D_o = \alpha\cdot D$, and that of non-overlay traffic is $D_n = (1-\alpha)\cdot D$. We use a randomly generated traffic demand in the following evaluations. We use the European Optical Network (EON) topology with 19 nodes and 39 bidirectional links (Fig. 3) for the physical topology. Each node has 8 input ports and 8 output ports and each fiber has enough wavelengths to accommodate lightpaths. That is, the number of lightpaths is constrained by the number of ports.

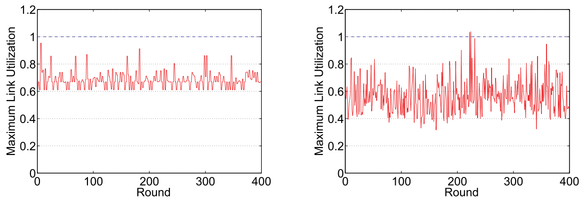
2.6 Degradation of Underlay Network Performance

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. 4. 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 α increases. With a small amount of overlay traffic ($\alpha = 0.1$), the maximum link utilization of 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 increases much more severely compared to the result of the fiber topology. Two factors are considered for this degradation. One is due to the interaction between overlay nodes, and another is due to the interaction between overlay routing and VNT control. We refer to the interaction between overlay routing and VNT control as the *vertical interaction* and the interaction between overlay nodes as the *horizontal*



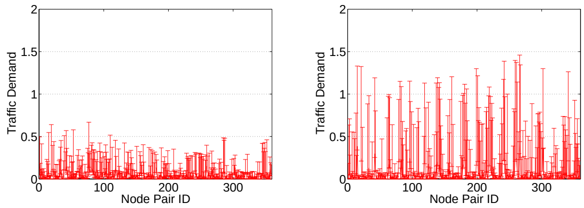
(a) Fiber topology (b) MLDA

Fig. 4 Maximum link utilization.



(a) Fiber topology (b) MLDA

Fig. 5 Fluctuation of maximum link utilization (α = 0.2, Total traffic: 10).



(a) Fiber topology (b) MLDA

Fig. 6 Fluctuation of traffic demand (α = 0.2, Total traffic: 10).

interaction. Note that only the horizontal interaction appears in the fiber topology since no VNT reconfiguration is made. In the case of 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.

2.7 Instability due to Coexistence of Two Routing

In this section, we show that the vertical interaction leads to instability of VNT control. Fig. 5 shows that the maximum link utilization depends on the rounds at which VNT control or overlay routing take their actions. As we described above, for both MLDA and fiber topology, the maximum link utilization gets high, if the amount of the overlay traffic is larger than 0.1. Therefore, we set α to 0.2 in this figure and observe the reason for the degradation mentioned above. When a VNT is dynamically controlled (i.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.

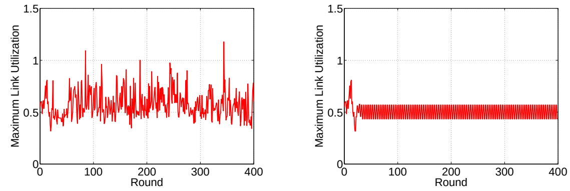
Fig. 6 shows the traffic demand for each node pair. The error bars show the maximum and minimum values of the traffic demand in the evaluation and a point in the bar indicates the average value. The horizontal axis represents the node pair ID that is specified uniquely by the source-destination pair. It is observed that the traffic demand fluctuates drastically when the VNT is dynamically controlled by MLDA. The vertical interaction degrades the stability and the performance of the network drastically. The main reason for this instability is that the VNT control algorithms generate VNTs according to the traffic demand. As shown in Fig. 6, overlay routing causes the extreme changes in the traffic demand. Since VNT control configures VNTs according to the traffic demand, the fluctuation of the traffic demand leads to a significant instability of VNT control.

3 Improvements in Stability of Network State

In this section, we apply *hysteresis* to VNT control to overcome the instability due to the vertical interaction.

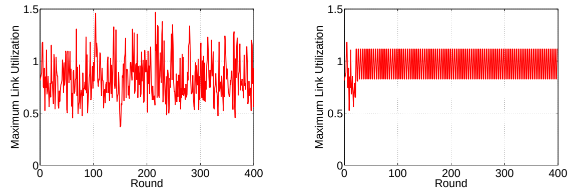
3.1 Utilization Hysteresis

Hysteresis is the property of systems that do not immediately react against changes in environments. This property is often used to



(a) No Hysteresis (b) Utilization Hysteresis

Fig. 7 Fluctuation of maximum link utilization (H = 0.4, α = 0.2, Total traffic: 10).



(a) No Hysteresis (b) Utilization Hysteresis

Fig. 8 Fluctuation of maximum link utilization (H = 0.4, α = 0.3, Total traffic: 10).

avoid routing fluctuation [8, 14, 17]. Since the instability appears in the maximum link utilization as presented in the previous section, we apply hysteresis to the maximum link utilization. We refer to this application of hysteresis as *utilization hysteresis*. Utilization hysteresis works as follows. First, we temporarily calculate the VNT, $C^h(t)$, using the current traffic demand $D(t)$. Then, we estimate the link utilization on $C^h(t)$, $U^h(t)$, 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 a hysteresis threshold 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.

3.2 Performance Evaluation

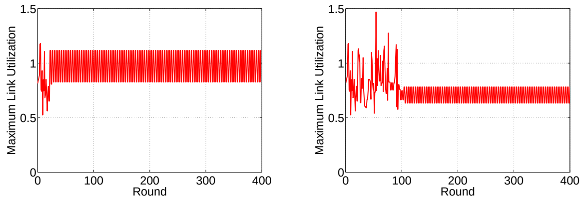
We use the same simulation model as presented in Section 2. In obtaining the following figures, the hysteresis mechanisms are not applied during the first 20 rounds to ignore the transient phase. Fig. 7 shows the fluctuation of the maximum link utilization. We set the hysteresis threshold H to 0.4. This figure clearly shows that the maximum link utilization with utilization hysteresis is stable compared to the results without hysteresis. We change the ratio of overlay traffic α from 0.2 to 0.3 in Fig. 8. Although the maximum link utilization of VNT control with utilization hysteresis is stable, the utilization with utilization hysteresis is higher than that without hysteresis. Due to the space limitation, we omit to show the result of other hysteresis threshold values. These results also indicate that utilization hysteresis does not always improve the maximum link utilization and the link utilization in the stable state does not depend on the hysteresis threshold H. The reason for this is that routes of the overlay network flap between approximately two routes if the VNT is fixed. Hence, 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.

4 Improvements in Network Performance

Applying utilization hysteresis to VNT control improves the stability of the network, but does not always improve the performance. In this section, we extend utilization hysteresis to improve both the stability and the performance.

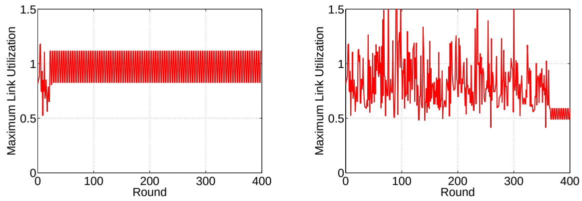
4.1 Two-State Utilization Hysteresis

We extend utilization hysteresis and propose *two-state utilization*



(a) Utilization Hysteresis (b) Two-State Utilization Hysteresis

Fig. 9 Fluctuation of maximum link utilization (k = 3.0, H = 0.4, α = 0.3, Total traffic: 10).



(a) Utilization Hysteresis (b) Two-State Utilization Hysteresis

Fig. 10 Fluctuation of maximum link utilization (k = 5.0, H = 0.4, α = 0.3, Total traffic: 10).

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. 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 utilization u_l and u_u are updated every time when VNT control is performed. 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 high maximum link utilization. Otherwise, utilization hysteresis is applied. Then VNT control again searches another stable state where the maximum link utilization is sufficiently low.

4.2 Performance Evaluation

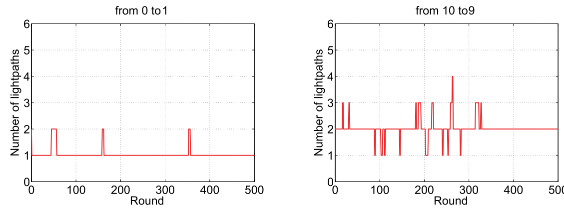
We evaluate two-state utilization hysteresis under the same simulation model as the previous section. The simulation parameters are set to the same ones as in Fig. 8. Figs. 9 and 10 show the fluctuation of the maximum link utilization in the case that k is 3.0 and 5.0, respectively. These figures clearly indicate that VNT control gets stable and the maximum link utilization is lower than that in Fig. 8. However, these figures also show that the convergence time, which is defined as the time until the VNT gets stable, becomes longer than that in Fig. 8. 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 the next section, we show another extension to make the convergence time shorter.

5 Fast Convergence of VNT Control

Two-state utilization hysteresis makes the convergence time longer, since two-state utilization hysteresis restricts the region where utilization hysteresis is applied. In this section, we introduce a *filtering* method to achieve the fast convergence.

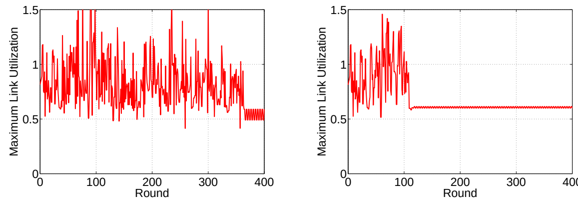
5.1 Filtering Method against Small Changes in VNT

We observe the number of lightpaths between node pairs. We select two node pairs that have the typical tendency that we will describe later and show the result in Fig. 11. The horizontal axis shows the rounds and the vertical axis shows the number of lightpaths between a node pair. The node ID in this figure is shown in Fig. 3. In Fig. 11(a), one lightpath is configured from the node 0 to the node 1 at the most of rounds, but at rounds 60, 160, and 350, two



(a) Node Pair (0, 1) (b) Node Pair (10, 9)

Fig. 11 Number of lightpaths (α = 0.3, Total traffic: 10, Number of ports: 8, k = 5.0)



(a) No Filtering (b) Filtering

Fig. 12 Fluctuation of maximum link utilization (Two-state utilization hysteresis, k = 5.0, α = 0.3, Total traffic: 10).

lightpaths are configured in a very short period. Finally, the number of lightpaths in this node pair converges to 1. In Fig. 11(b), although the number of lightpaths also decreases or increases in a very short period, two lightpaths are configured at almost all rounds and the number of lightpaths finally converges to 2. We find these results in more than half of all node pairs. These many small changes in the number of lightpaths result in a large change in the VNT.

Therefore, we introduce a filtering method to reduce those small changes in the number of lightpaths and achieve the fast convergence of VNT control. The VNT control method with the filtering method maintains the history of the number of lightpaths that the VNT control method calculated, that is, $C^h(t) = \{c^h_p(t)\}$ described in Section 3. Here, we maintain the history of the past 20 rounds of the VNT control method, $(C^h(t-2), C^h(t-4), \ldots, C^h(t-40))$. If n lightpaths were configured between a node pair p at more than 80% rounds in this history, the number of lightpaths between p is set to n even if $c^h_p(t)$ is different from n.

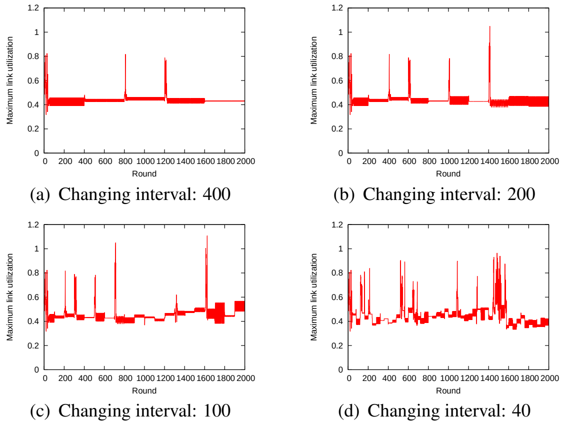
5.2 Performance Evaluation

We evaluate the filtering method under the same simulation environments as those in the previous section. The simulation parameters are set to the same ones as in Fig. 10. The convergence time in Fig. 12(b) is 110 while that in Fig. 12(a) is 360. We also omit to show other results due to the space limitation, but other results show that the filtering method reduces the convergence time.

6 Adaptability for Changes in Traffic Demand

Both the hysteresis mechanism and the filtering mechanism aim at improving the stability of VNT control by reducing unnecessary changes in the VNT. In general, these types of approaches degrade the adaptability for the changes in the traffic demand, since the VNT designed for the old traffic demand remains. In this section, we show the adaptability of our method for the changes in the traffic demand.

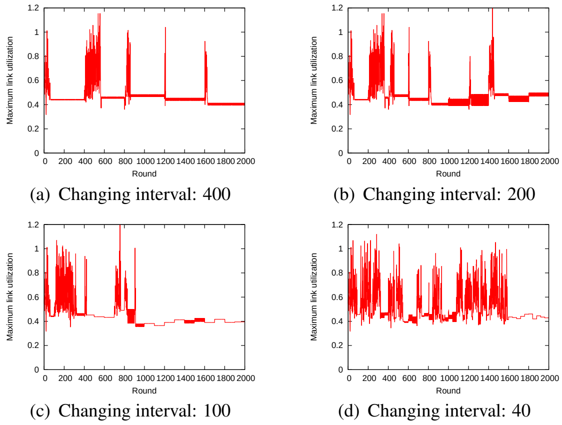
For evaluating the adaptability, we randomly regenerate the traffic demand at the same interval with holding the sum of the traffic demand constant. We refer to this interval as the changing interval. Other simulation conditions are the same as those in the previous section. Fig. 13 shows that the maximum link utilization depends on the rounds for k = 3.0. In the case that the changing interval is 40 (i.e., 20 VNT reconfigurations) VNT control follows the almost all changes in the traffic demand, but only at the round 1440 and 1480, VNT control does not converge until the next traffic change occurs. If the changing interval is longer than 40, VNT control converges



(a) Changing interval: 400 (b) Changing interval: 200

(c) Changing interval: 100 (d) Changing interval: 40

Fig. 13 Fluctuation of maximum link utilization (Two-state utilization hysteresis, filtering, α = 0.2, Total traffic: 10, Number of ports: 8, k = 3.0).



(a) Changing interval: 400 (b) Changing interval: 200

(c) Changing interval: 100 (d) Changing interval: 40

Fig. 14 Fluctuation of maximum link utilization (Two-state utilization hysteresis, filtering, α = 0.2, Total traffic: 10, Number of ports: 8, k = 5.0).

although the maximum link utilization fluctuates in a short period after the traffic change occurs. We next evaluate the adaptability for k = 5.0 in Fig. 14. VNT control does not follow the changes in the traffic demand in the case that the changing interval is 40. If the large k is used, the region where hysteresis is applied becomes narrow and therefore the convergence time becomes longer. This also results in the degradation of the adaptability for the traffic changes. In the case that the changing interval is 100, VNT control follows the almost all changes in the traffic demand except at the round 200. Although our methods do not follow the extremely heavy changes in the traffic demand, they show the acceptable adaptability. The reason for this is that VNT control with our proposals reconfigures its VNT immediately if the performance of the VNT is degraded due to the changes in the traffic demand.

7 Conclusion

In this paper, we investigated the interaction between VNT control and overlay routing. We revealed that this interaction causes high fluctuations in traffic demand, which leads to a significant instability of VNT control. To overcome the instability and to make VNT control more stable, we proposed utilization hysteresis for VNT control. We found that utilization hysteresis improves the stability, but does not always improve the maximum link utilization. We therefore proposed two-state utilization hysteresis that applies utilization hysteresis only when the maximum link utilization is sufficiently low. Simulation results indicated that two-state utilization hysteresis improves both the stability and the maximum link utilization. However, the convergence time becomes longer. To achieve the fast convergence, we introduced the filtering method to VNT control. Through simulations, we showed that the filtering method makes the convergence time shorter. Both the hysteresis method and the filtering method aim at improving the stability of VNT control by reducing unnecessary changes in the VNT. Finally, we show that our approaches achieve the good adaptability for the changes in the traffic demand, since VNT control with our proposals reconfigures VNTs immediately if the maximum link utilization gets high due to the traffic change.

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