New Routing Methodology Focusing on the Hierarchical Structure of Control Time Scale

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Abstract: We present a new routing methodology that focuses on the hierarchical structure of a control time scale. The key concept of this study is to simultaneously implement both multiple routing protocols: OSPF routing (shortest-path) and MLB routing (multi-path). By considering the difference in their control time scales, we construct a new routing scheme that deals with sudden changes in network conditions. That is, we design an architecture that basically allocates packets to the shortest path route and simultaneously allocates packets to an alternative route when congestion occurs. Furthermore, using simulations, we have also shown that this methodology achieves more efficient use of the network and significant improvements in end-to-end delays. We believe this methodology will pave the way for hierarchical approaches based on the control time-scale methodology.

Key–Words: hierarchical routing, control time scale, OSPF, MLB routing

1 Introduction

Today, information systems are an extremely important social infrastructure, and therefore require a high-level of reliability. At the same time, information systems are becoming larger, more complex, and faster; hence it has become very difficult for human beings to completely understand and control their behavior.

A hierarchical structure is employed by an information system's controlling architecture with each protocol for "each function." It is appropriate to control the structure for implementing each function in a system. However, despite its advantages for implementation, the hierarchical structure of an information system for each function is not necessarily the most adequate. Specifically, it is not necessarily the most suitable approach when it comes to appropriately controlling and operating an information system.

Contrary to the hierarchical structure for each function, we have proposed a series of studies toward a "**New hierarchical structure based on a control time scale**" [1, 2, 3, 7] for various control protocols required for an information system. With this new approach, we have proved that it is fundamentally possible to accurately control and operate an information system that continues to grow larger, faster, and more complex. It is also the result of our pursuit of a new basic architecture. With the hierarchical approach regarding the time scale of each protocol, it is expected to naturally incorporate extremely high speed functions such as packet control to the functions controlled in the human time scale, whilst retaining a proper complementary relationship between each hierarchy.

In this study, as an example of the methodology featured by the "Hierarchical approach with control time scale," we have constructed a new IP routing methodology. Specifically, we are going to propose a routing methodology that consists of two hierarchies: an upper hierarchy that assumes normal behavior and determines comprehensive routing (long time scale), and a lower hierarchy that allocates packets to an alternative route when congestion occurs (short time scale).

When this hierarchical approach is conducted with a control time scale, it is impossible to collect a wide range of information over the relevant time scale. As a result, it becomes necessary to separately run each hierarchy's protocol. Figure 1 shows a conceptual diagram of each different time-scale hierarchy. In a short time-scale hierarchy, there are many detailed protocols, and each range of the individual protocol is limited. On the other hand, in a long time-scale hierarchy, detailed network protocols are omitted, and only a rough structure appears where it shows a wide range of individual protocols. In both hierarchies, the protocols in each subject time scale are dispersive in the sense that it "impacts the controllable range on the basis of the available information".

For this reason, in this study, we have adopted the MLB routing methodology for the lower hierarchy that controls local detours [6]. This methodology that we have proposed is a multipath routing protocol that could be implemented as a distance-vector protocol. It is common knowledge that in the distance-vector protocol, the routing protocol is established by frequently repeating the information exchange only between neighboring routers. Hence, a "protocol with a narrow range and short time scale," is required for the lower hierarchy. Additionally, it can be expected to quickly bypass the congested area by securing multiple routing with its multipath function. Meanwhile, we have adopted OSPF [5] that is widely common as an existing methodology for the upper hierarchy because of its compatibility with the current IP network.

In this study, the hierarchical approach based on a time scale is not limited to the routing protocol. In general, it requires careful examination as to whether the protocols in each hierarchy would interfere with each other and whether the multiple hierarchies would create a complementary effect. In other words, this study also aims to verify the preventive effect from interference and the complementary function by the hierarchical structure of the control time scale.

This paper is structured as follows. In Section 2, we explain the formulation of the MLB routing methodology. In Section 3, we propose and evaluate the hierarchical routing methodology, in which two different time-scale routing schemes are simultaneously employed. In Section 4, we present our evaluation of the characteristics and effectiveness of the routing protocol that we propose through a simulation test. Finally, we discuss our future goals (Section 5).

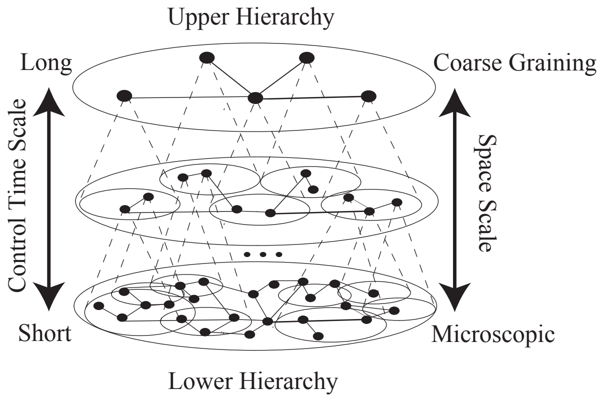


Figure 1: Conceptual Diagram of a Hierarchical Time scale

2 MLB Routing Control Technique

In this section, we outline the MLB routing control technique [6] proposed by the authors.

2.1 Formularization of MLB Routing Control

We consider a directed graph $G = (N, E)$, where N = the set of nodes and E = the set of links. We denote the link cost from link $i \to j$, c_{ij}. Each node v may be the origin, destination host, or the router, and the total of neighboring nodes is expressed as $nbr(v)$.

We consider packet p to traverse from node o to node d, and we consider that the path is determined based on some standard. Theset of paths to the candidate path $o \to d$ is given as Φ^{od}. At that time, the probability of using the rth path is given as

$$P_r^{od} = \frac{\exp\left[-\gamma C_r^{od}\right]}{\sum_{r \in \Phi^{od}} \exp\left[-\gamma C_r^{od}\right]}. \tag{1}$$

Here, C_r^{od} refers to the cost of the rth path from $o \to d$, and in this research, it is given as the sum of the individual link costs that form the path:

$$C_r^{od} \stackrel{\text{def.}}{=} c_{ov_1} + \sum_{l=1}^{\Lambda-1} c_{v_l v_{l+1}} + c_{v_\Lambda d}. \tag{2}$$

Also, the rth path is given as $o \to v_1 \to v_2 \to \cdots \to v_\Lambda \to d$.

In MLB routing control, when the path total Φ^{od} is given as "total possible paths", the network flow formed is of equal value with the Markov distribution below [4] as proved by (1):

$$p_d(j|i) = \exp\left[-\gamma c_{ij}\right] \frac{W_{jd}}{W_{id}}, \tag{3}$$

$$W_{id} \stackrel{\text{def.}}{=} \sum_{r \in \Phi^{id}} \exp\left[-\gamma C_r^{id}\right] + \delta_{id}. \tag{4}$$

$p_d(j|i)$ is the transition probability of the packet with node d as host being transmitted from $i \to j$, and δ_{id} is the Kronecker delta. In the formularization above, clearly

$$\sum_{j \in nbr(i)} p_d(j|i) = \frac{\sum_{j \in nbr(i)} \exp\left[-\gamma c_{ij}\right] W_{jd}}{W_{id}} = 1 \tag{5}$$

is fulfilled. Through the existence of a Markov distribution of equal value, MLB routing control through each route is possible. Specifically, each router can stochastically transmit packets based on the transition probability $p_d(j|i)$ of (3).

In addition, we note the fact that $p_d(j|i)$ can be determined without depending on origin node o. In other words, the routing table of MLB routing control, as with existing protocols, is shown to allow separate calculation of each destination host.

2.2 Method for Calculating Transition Probability

To decide the concrete value of transition probability $p_d(j|i)$, it is necessary to calculate the value of W_{id}. Now, we will consider an $N \times N$ matrix $\boldsymbol{A}$ given as the following for each element:

$$a_{ij} = \begin{cases} \exp\left[-\gamma c_{ij}\right] & \text{(When link } i \to j \text{ exists)} \\ 0 & \text{(All other cases)} \end{cases} . \tag{6}$$

In addition, $\boldsymbol{A}$ is considered to fulfill the Haskins-Simon conditions. Now, W_{id} is calculated as follows:

$$\boldsymbol{W} = [\boldsymbol{I} - \boldsymbol{A}]^{-1} . \tag{7}$$

Each element of $\boldsymbol{W}$ is

$$W_{ij} = \sum_{r \in \Phi^{ij}} \exp\left[-\gamma C_r^{ij}\right] + \delta_{ij}. \tag{8}$$

As mentioned above, by distinguishing matrix $\boldsymbol{A}$, it becomes clear that the values of W_{id} and thus $p_d(j|i)$ can be calculated. As $\boldsymbol{A}$ can be collected as one part of the topology information, the above discussion shows that MLB routing control can be implemented as a linkstate protocol.

Also, MLB routing control can be implementedas a distancevector protocol. Specifically, we note that the for W_{id} the below recursive formula

$$\begin{aligned} \boldsymbol{W} &= \boldsymbol{I} + \boldsymbol{A}\left(\boldsymbol{I} + \boldsymbol{A} + \boldsymbol{A}^2 + \boldsymbol{A}^3 + \cdots\right) \\ &= \boldsymbol{I} + \boldsymbol{A}\boldsymbol{W} \end{aligned} \tag{9}$$

is in effect, and (9) is the same value as

$$W_{id} = \sum_{j \in nbr(i)} \exp\left[-\gamma c_{ij}\right] W_{jd} + \delta_{id}. \tag{10}$$

Recurrence formula (10) shows that W_{id} for each router can be determined through the W_{id} of neighboring routers. Thus, W_{id} can be calculated through a Bellman-Ford algorithm. In other words, MLB routing control canalso be implemented as a distancevector system.

3 Hierarchical Routing Protocol based on time scale

In this section, we present an example of a network protocol that focuses on the hierarchical approach with a control time scale. This is done through the formulation of a routing methodology, in which our proposed MLB routing (lower hierarchy) and the existing routing protocols such as OSPF (upper hierarchy) are combined.

3.1 Categorization of a routing methodology of a control time scale

The objective of this study is to construct a routing algorithm that can rapidly deal with the network's status changes under the concept of "hierarchical approach with time scale" for computer networking. We start by summarizing the characteristics of the existing routing methodology (especially OSPF routing) and the MLB routing methodology that we proposed in Section 2.

OSPF routing is one of the most practical routing methodologies used today. In OSPF routing, it is well known that the routing table is constructed on the basis of a link-state protocol. With the link-state protocol, each router can store the network (topology) information at a relevant point in time but the update interval of the routing table is long. Also, because OSPF routing basically allocates packets to the shortest path route (partially containing equal-cost multipath functions), the order of the packets' arrivals and the forwarding path are typically stable. Therefore, with respect to the proposed concept of a hierarchical approach with a control time scale, OSPF routing contains long control-time intervals. Therefore, it is categorized with the "upper hierarchy" that requires slow transitions.

Meanwhile, we examine the implementation of MLB routing, proposed in the previous section, as a distance-vector protocol. First, with the distance-vector protocol, the update interval of the routing table is shorter than that of the link-state protocol because the routing table is constructed by repeated information exchanges between neighboring routers. Furthermore, since MLB routing is a multipath routing method that utilizes multiple paths, load balancing in the network can be realized. However, the characteristics of a short update interval and multiple path distribution lead to frequent path changes. Hence, with respect to the proposed concept of hierarchical approach with a control time scale, it can be concluded that MLB routing (with a distance-vector protocol) contains short control-time intervals. Therefore, it is categorized with the "lower hierarchy" requiring quick transitions. Table 1 indicates the above mentioned

Table 1: Comparison of OSPF and MLB routings

Items	OSPF	MLB
Protocol length	Long	Short
NW Information	Many	Few
QTY of Candidate routing	Few	Many
Newness of routing information	Old	New

comparison between OSPF and MLB routings.

3.2 Overview of hierarchical routing of a control time scale

As proved in the previous section, there is a significant difference between the characteristics of OSPF routing and MLB routing. This is especially true from the perspective of the hierarchical structure of time scale; OSPF routing pertains to a slow algorithm with relatively long intervals, while MLB routing (distance-vector protocol) pertains to a quick algorithm with short intervals. Next, we proceed to discuss hierarchical routing by taking advantage of both characteristics that pertain to different control time scales.

The routing path of IP networks should be stable as much as possible to preserve the order of data arrival and ease of control. Therefore, many of the existing routing methodologies have adopted the shortest path route. However, the shortest path route is vulnerable to local congestion or sudden link termination (although several countermeasures have been developed). To solve such sudden network issues, it would be effective to allocate packets to alternative routes to avoid the problematic area. In fact, multipath routing can be regarded as a methodology to prepare multiple alternative routes in such cases.

Hence, if multipath routing changes for the network, as in cases when congestion, etc. can be locally implemented while maintaining the shortest-path routing as the main protocol, it would become possible to implement a routing protocol that combines the advantages of both types of routing. For such an implementation, it is recommended that shortest-path routing pertains to a long control time scale to build a comprehensive routing and that multipath routing pertains to short control time scales to handle sudden changes such as congestion.

From the above mentioned perspective, in this study, we are aiming to design a routing methodology that could immediately handle network changes by simultaneously implementing OSPF routing as the main protocol (upper hierarchy) and MLB routing that supports detour routes (lower hierarchy). Specifically, we have considered providing each node with two kinds of routing tables that were constructed in each methodology. Additionally, we have attempted to construct a preferable protocol by appropriately adjusting (i) the update interval of routing tables and (ii) the choice of routing table that each router employs.

3.3 Hierarchical Routing's System Model

We are going to explain the methodology of the hierarchical routing system model that we propose in this study. First, we present a regular IP network that consists of multiple nodes and links as a system model. Then, we assume that all nodes could be the source and destination, and each node should transmit the data based on their own routing table.

As previously mentioned, with our proposed routing system, each node owns two distinct routing tables for OSPF and MLB routing. First, we will explain each routing table's methodology and the update interval. For OSPF routing, which is in the upper hierarchy, a long update interval should be set because it is to be implemented with the link-state protocol and it pertains to comprehensive routing. The particular update is to be implemented when a drastic change occurs in the network, apart from regular intervals.

On the other hand, for MLB routing that is in the lower hierarchy, its update interval should be set to be shorter than that of OSPF routing because it is basically used to update the routing table with a distance-vector protocol. This allows MLB routing to detour the area, where sudden changes, such as congestion, occurred in the network. It can be expected that by frequently updating the routing table with the distance-vector protocol, the sudden change in the network is immediately reflected to the routing table. However, for the initial routing table configuration, it takes a long time to converge with a distance-vector protocol. Hence, in this study, the link-state information collected in OSPF routing was utilized, and inverse matrix calculation was made for batch data input.

Second, we will explain how to properly use the two different routing tables created by both routing methodologies depending on the network state. Basically, in this study, our proposed system is designed to handle the area where no congestion occurred with OSPF routing (shortest-path) and the area where congestion or trouble occurred with MLB routing (multipath). Therefore, it is necessary for each node to distinguish whether congestion occurred and then select the appropriate routing table to use. Figure 2 indicates the system model that summarized the above mentioned algorithm. Figure 3 indicates the structural diagram of the simultaneous implementation.

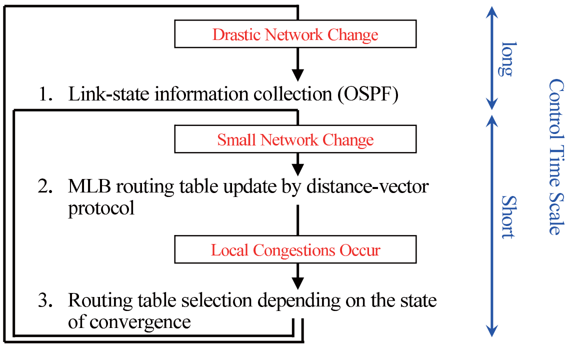


Figure 2: Structural Diagram of Hierarchical Routing of time-scale

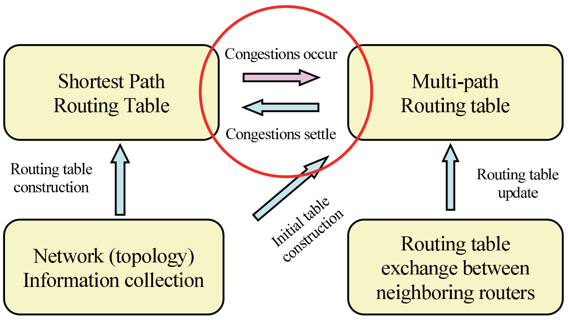


Figure 3: Simultaneous Implementation of a multiple routing protocol

3.4 Switchover Rule

Finally, we will discuss how each node could judge whether the network has encountered congestion, that is, the routing table's switchover rule (red sections in Figure 3).

The most generic judgment criterion for the congestion node would be

[Criterion 1] Whether packets exist inside a node queue.

If packets are accumulated inside the queue, it means that congestion has occurred inside the relevant node. Hence, it can be considered that the above rule is effective for switching from OSPF routing to MLB routing.

Our proposed methodology contains both OSPF routing's shortest-path routing table and MLB routing's multipath routing table. A network's status change, such as congestion, etc., is reflected in the multipath routing table faster than it is in the shortest-path routing table because of the time-scale difference. Therefore, it can be assumed that congestion occurs inside (or at least near) the node, in which both routing tables diverge significantly.

Considering the aforementioned perspectives, it can be determined that if the characteristics of the shortest-path routing and multipath routing tables are significantly different, it is more likely that congestion occurred inside the node. In this study, we have focused on designated next routers in the shortest-path routing table (hereafter called "shortest next-routers") and adopted the following criteria as the candidate rules:

[Criterion 2] In a multipath routing table, whether the choice probability of the shortest next-router is ranked at the top.

[Criterion 3] In a multipath routing table, whether the choice probability of the shortest next-router is ranked at the bottom.

Also, using similar reasoning, we assume that the following criterion is valid:

[Criterion 4] In a multipath routing table, whether the choice probability of the shortest next-router is over the threshold.

In this study, we have changed the threshold of choice probability by 0.1, i.e., from 0.1 to 0.9.

Finally, we discuss the criterion that focused on the multipath routing table's choice probability formula. As shown in equation (3), the choice probability $p(j|i)$ from node i to node j mainly depends on $\exp\left[-\gamma c_{ij}\right] W_{jd}$. This index can be regarded as the easiness of overall arrival when node j is chosen. Hence, if congestion occurred at the end of node j, the value should change significantly. Owing to the above, in this study, we have adopted the following criterion as well:

[Criterion 5] In the multipath routing table, whether the value of $\exp\left[-\gamma c_{ij}\right] W_{jd}$ has changed from the initial value over a certain threshold (%).

In the next section, we will explain the simulations of the above [Criteria 1-5] together with our performance evaluations.

4 Simulation Evaluation

In this section, we present the simulation evaluation of the hierarchical routing methodology with the proposed time scale of the previous section.

4.1 Simulation Methodology

We ran simulations using the following methodology. To begin with, we generated network topologies using the Waxman model [8]. Specifically, we randomly distributed 100 nodes on a two-dimensional plane and created a network. The number of links was set to a total of 392. The Waxman parameter values were set at $\alpha = 0.5$ and $\beta = 0.15$.

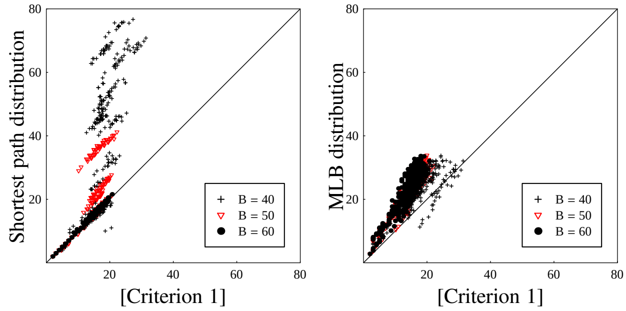
We set the standard link delay cost d_{ij} in proportion to the separation distance of two nodes. Additionally, we set each link bandwidth $B = 40, 50$, and 60 [packets/unit time] in three options. Furthermore, 20 of the top left nodes were set as origin nodes, while 20 of the bottom right nodes were set as the destination nodes. Within the unit time period of 200, every node pair sent/received 1 [packet/unit time], which means that 400 packets were generated in each unit time. The simulation continued until all data packets had reached their destinations. To compare the performance of MLB-routing with the shortest-path routing (OSPF), we set the maximum queue size of each network node to infinity. (In other words, no packet was lost in any node.) This assumption enables us to make meaningful comparisons under two different routing protocols. Finally, for MLB routing, we set $\gamma = 1.0$, which is lower than the normal value, because the exact value cannot be calculated.

4.2 Switchover with buffer queue detection

First, we have examined the simulation result from the case of [Criterion 1]. Setting [Criterion 1] as the routing table's switchover criterion for simultaneous implementation, we have individually compared the average delay cost[1] with the distribution of the shortest-path routing table only (OSPF) and the distribution of the multipath routing table only (MLB). Figure 4 summarizes the comparison.

As seen in Figure 4, simultaneous implementation would reduce the average delay cost with most origin/destination node pairs comparing with either shortest-path distribution only or multi-path distribution only. In other words, it was proved that we could expect an overall improvement in performance by simultaneously implementing both OSPF and MLB routing protocols and comparing with the case where each routing protocol is individually implemented. More significantly, a preferable network protocol was achieved even if buffer queue detection, which is easy to implement, is adopted as the routing table's switchover criterion. From the above findings, it can be concluded that our proposed methodology in

[1]Jitter (standard deviation) comparison was conducted. However, owing to the article space limitations, it has been omitted.



(a) Comparison with OSPF (b) Comparison with MLB

Figure 4: Comparison of average delay cost when introducing [Criterion 1]

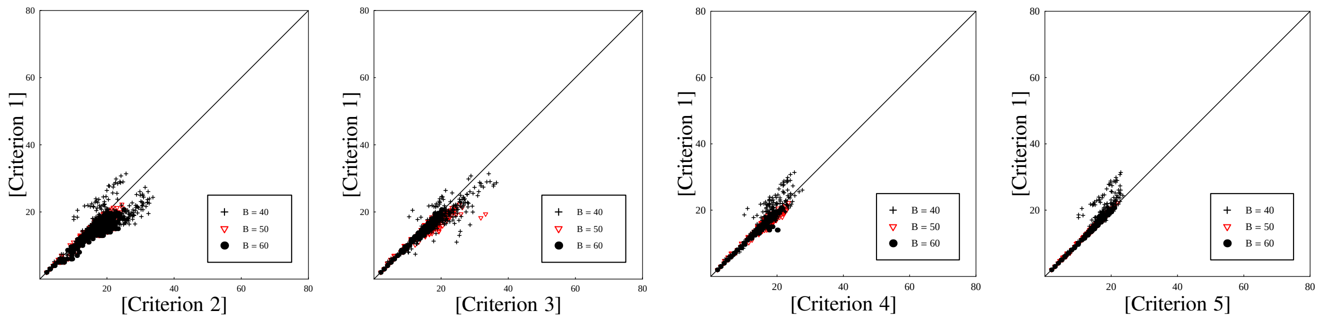
this study is effective when it comes to the efficient utilization of a network.

4.3 Switchover with other criteria

As mentioned in the previous section, we proved that the routing table's switchover, which is implemented on the basis of [Criterion 1], could reduce the average delay cost as a whole. However, if one examines the comparison with multipath distribution in Figure 4-(b), one would notice that simultaneous implementation deteriorated the delay cost for some node pairs. That is, we proved that buffer queue detection is not sufficient to completely avoid congestion. Therefore, we have made similar comparisons with [Criterion 2] to [Criterion 5] to examine the effectiveness. Specifically, we have compared each criterion with the shortest-path distribution, multi-path distribution, and the case when [Criterion 1] is set as a switchover criterion. Owing to space limitations on the paper, Figure 5 only shows the results of the average delay cost comparison when [Criterion 1] is set as the switchover criterion.

Figure 5-(a) & (b) indicate the results of comparison with [Criterion 1] if [Criterion 2] and [Criterion 3] were set as the hierarchical routing's switchover criteria. As easily proven with these results, there was no improvement in the average delay cost, and in fact, it deteriorated with the addition of more node pairs. Hence, it can be said that [Criterion 2] and [Criterion 3] are not appropriate for a congestion detection criterion with simultaneous implementation.

Figure 5-(c) indicates the result of a comparison with [Criterion 1] if [Criterion 4] was set as the hierarchical routing's switchover criterion. From the result, it can be easily said that the average delay cost was improved with many node pairs compared with [Criterion 1]. Thus, it can be concluded that more desir-



(a) Comparison with [Criterion 2]
(b) Comparison with [Criterion 3]
(c) Comparison with [Criterion 4]
(d) Comparison with [Criterion 5]

Figure 5: Comparison of average delay cost with [Criterion 1]

able network protocols can be generated if hierarchical routing is implemented by setting [Criterion 4] as the switchover criterion. However, a new threshold of choice probability needs to be determined for [Criterion 4]. This result is based on a hypothesis where the threshold is assumed to be 10%. Figure 6 shows the relationship between our routing performance and the threshold of [Criterion 4]. In paticular, we calculated the relative frequency that average delay costs of [Criterion 4] exceed those of OSPF, MLB, and [Criterion 1]. From Figure 6, in the simulations with 20%-90% thresholds, we could not obtain sufficient improvement. Therefore, we assume that [Criterion 4] is not the most appropriate criterion when it comes to the threshold's degree of freedom.

As is evident from Figure 5-(d), when [Criterion 5] is set as the switchover criterion, there are more improvements than [Criterion 4] of Figure 5-(c), and the performance was further improved with every node pair. Also, for [Criterion 5], we have made individual comparisons with the shortest-path distribution only and the multipath distribution only and verified that it improved performance. Likewise, a threshold, which is supposed to be the "change ratio based on the initial value," needs to be reset for [Criterion 5]. Figure 7 indicates the relationship between our routing performance and the threshold of [Criterion 5], that is, the relative frequency that average delay costs of [Criterion 5] exceed those of OSPF, MLB, and [Criterion 1]. From Figure 7, the fevorable result was mutually confirmed when the threshold was set from 10% to 40%. Hence, it was verified that [Criterion 5] is more effective than [Criterion 4] at detecting congestion, based on the threshold's degree of freedom.

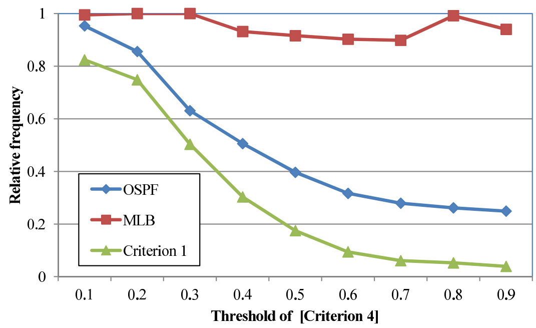


Figure 6: Simultaneous Implementation of a multiple routing protocol

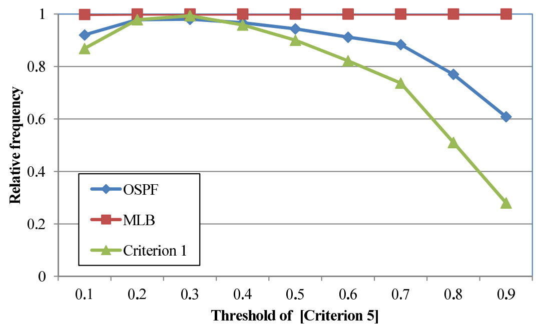


Figure 7: Simultaneous Implementation of a multiple routing protocol

5 Conclusion and Future Goals

In this study, we have proposed a new routing methodology, which employed a hierarchical approach with a control time scale by simultaneously implementing OSPF routing (shortest-path) and MLB routing (multi-path). The focal point of this methodology is that the simultaneous implementation of two different routing protocols enables stable network control with comprehensive shortest-path routing and flexible routing that is capable of avoiding sudden congestion. Furthermore, through simulations, we have proved that simultaneous implementation could improve the average delay cost and jitter by comparing with the implementation of each individual routing protocol. Our future goal is to further investigate the effective switchover rules and other criteria.

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