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Stability Evaluation of a Dynamic Traffic Engineering Method in a Large-Scale Network

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SUMMARY As use of the Internet continues to spread rapidly, Traffic Engineering (TE) is needed to optimize IP network resource utilization. In particular, load balancing with TE can prevent traffic concentration on a single path between ingress and egress routers. To apply TE, we have constructed an MPLS (Multi-Protocol Label Switching) network with TE capability in the JGN (Japan Gigabit Network), and evaluated dynamic load balancing behavior in it from the viewpoint of control stability. We confirmed that with this method, setting appropriate control parameter values enables traffic to be equally distributed over two or more routes in an actual large-scale network. In addition, we verified the method's effectiveness by using a digital cinema application as input traffic.

key words: *traffic engineering, MPLS, dynamic load balancing, network congestion*

1. Introduction

The development of high-speed IP networks is expected to lead to an explosive increase in IP traffic as use of the Internet continues to spread rapidly. In current IP networks, routes are controlled by routing protocols such as the Open Shortest Path First (OSPF) protocol. However, these protocols simply find the shortest route by using Dijkstra's algorithm [1] and don't attempt to find a route by employing traffic characteristics, available bandwidth, and so on. As a result, IP traffic is concentrated on a specific route and network congestion can occur. Traffic engineering (TE) technology [2] with Multi-Protocol Label Switching (MPLS) [3]–[5] has garnered much attention as one technology for solving this problem. TE technology aims at optimized network performance through such means as maximized throughput and minimized packet loss and delay.

In the future, network resources will need to be used more efficiently to deal with the growing use of broadband applications in high-speed IP networks. For example, the transfer rate of digital cinema applications [6] ranges from tens to hundreds of megabits per second. Recently, a load balancing method based on an MPLS router (a Label Switching Router, or LSR) that employs TE technology to prevent network congestion has been reported [7]–[12]. In our work, we have focused on developing a dynamic load balancing method [7]–[10] that autonomously shifts traffic concentrated on a specific link to another link with a low utilization rate. This method reduces the network operation cost and permits flexible path setup, because it enables the MPLS router to find an optimum route autonomously when network congestion is detected. We have been able to advance the development of LSRs in which the dynamic load balancing method is implemented. The method's effectiveness has not previously been evaluated in an actual network, although quantitative evaluations were done through simulation [8] and other methods [11], [12]. Consequently, we set up LSRs, each of which had the dynamic load balancing method implemented, at four access points, and we constructed an MPLS network over the Japan Gigabit Network (JGN) [13], which is a super-high-speed, large-scale network. We obtained appropriate parameter values by evaluating the dynamic load balancing method when applied to this actual network.

The dynamic load balancing method is described in Sect. 2, and the experimental environment and network models are described in Sect. 3. In Sect. 4, we discuss the effect on traffic characteristics of changing various control parameters. In particular, we evaluate the method's behavior from the viewpoint of control stability. In Sect. 5, we consider a demonstration system in which an actual digital cinema application was used to confirm the method's effectiveness.

2. Dynamic Load Balancing

2.1 Outline

An MPLS network consists of edge and core LSRs, and Label Switched Paths (LSPs) are set up between the ingress-edge and egress-edge LSRs. The dynamic load balancing method, as described in Ref. [9], autonomously distributes IP flows to two or more LSPs in accordance with the network's traffic situation, thus

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preventing network congestion. This method comprises traffic collection and notification functions, alternative route-finding and path set-up functions, and an IP-flow distribution function. The core LSR executes only the traffic collection and notification functions, while the edge LSRs execute all functions. An alternative-route (engineering-route) LSP is set between the ingress-edge and egress-edge LSRs; thus, the IP flow is distributed between the default route and the engineering route.

(1) Traffic collection and notification functions
Each LSR measures the utilization of the output link at constant intervals, and the collected statistical information is reported to the edge LSRs on the ingress side by periodic flooding with OSPF Opaque LSAs (Link State Advertisements). The edge LSRs construct a database by using the information reported from all the LSRs. Therefore, since they know all link statistics, they can examine the traffic situation of each link along an LSP and detect which LSPs suffer from network congestion.

(2) Alternative route-finding and path set-up functions
The edge LSRs judge whether the amount of traffic on a link in a certain specific route exceeds the network congestion threshold. If it does, they find an engineering route. This function improves upon Dijkstra's algorithm and finds the calculated route with the most available bandwidth. Afterwards, an LSP is explicitly set up by using the RSVP-Tunneling Protocol (RSVP-TE) [14], which is a signaling protocol.

(3) IP-flow distribution function
The edge LSRs distribute IP flows between the LSP of the engineering route and the LSP of the default route so as to equalize the utilization of each link making up each LSP. The LSP along which IP flows are distributed is determined according to a hash value calculated from IP header information, such as the destination IP address (Fig. 1(a)). The edge LSR divides the range of the obtained hash values for all LSPs that have already been set up. Here, the range of hash values is 0-65535 because we used CRC16 calculation. We call this delimitation the hash boundary value. This value is moved according to the amount of traffic on the LSP.

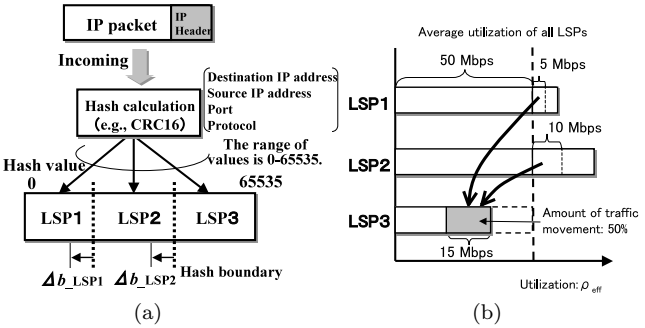


Fig. 1 IP flow distribution processing (50% move granularity).

Dynamic load balancing among LSPs becomes possible because the edge LSR moves the hash boundary value according to the LSP utilization. Specifically, the load is adjusted by moving the hash boundary so that the effective utilization (ρ_{eff}) of each LSP approaches the average load for all LSPs (Fig. 1(b)). This corresponds to moving some of the IP flows carried on one LSP to another LSP. The edge LSRs periodically calculate the amount of traffic movement based on the statistical information. Therefore, the amount of traffic can be distributed dynamically.

2.2 Control Parameters

In executing this dynamic load balancing, the control parameters greatly influence the traffic behavior. Important control parameters include the following.
- Move Granularity: This represents the amount of traffic that can be moved to shift IP flows to other LSPs, and it determines the hash boundary value. The amount of hash boundary movement Δb_LSPi is given by

$$\Delta b\_LSPi = \frac{move\_traffic\_LSPi}{\sum \rho eff\_LSPi} \times 65535 \times move\_granularity. \quad (1)$$

Here, move_traffic_LSPi is the difference between the average utilization for all LSPs and the utilization of LSPi. The integer value 65535 represents the range of values that can be accepted by the hash calculation. The value of the move_granularity is less than 1.0 and is used when the edge LSRs calculate the amount of traffic that can be moved each time. For example, if this value is 0.5, the hash boundary is moved by only 50% of the calculated amount of hash movement (Fig. 1(b)). We write this as move granularity: 50%.
- Smoothing Factor: This indicates a smoothing coefficient (N). Each LSR smoothes the measured data to prevent network congestion by detecting rapid traffic changes such as burst traffic. This smoothing is accomplished by averaging statistical information for the past N times.
- Flooding Interval: This is the periodic flooding interval for the statistical information reported from each LSR to the edge LSRs on the ingress side.
- Network Congestion Threshold: This is the threshold used to judge whether network congestion has occurred, based on the periodic statistical information. It indicates the ratio at the link speed.

2.3 Distributed Processing Concerns

This method is executed through distributed processing controlled independently by each LSR. Therefore, we have to consider two problems that could arise regarding network control.

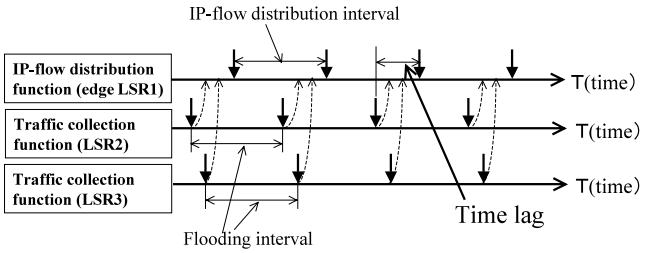


Fig. 2 Distributed processing problems.

- The traffic collection function of all LSRs and the IP flow distribution function of the edge LSRs are executed through distributed processing. These two functions cannot be synchronized because there is a time lag with respect to the transmission delay and the device processing time (Fig. 2).
- When network congestion occurs in one link, the IP flow distribution process is executed by multiple edge LSRs. In this case, the LSRs might over-control the load balancing execution by all acting at the same time.

With respect to the first problem, the IP flow distribution processing of the edge LSRs might result in over-control because of the time lag. This would especially be a concern in a large-scale backbone network as carrier IP networks are constructed to provide various IP services. Also, as the network expands globally, the transmission distances will increase. Therefore, the transmission delay will become a greater problem in a large-scale network.

As a first step, we focused on the first problem of over-control to confirm the basic effectiveness of our method. We examined the traffic characteristics in an actual large-scale network when various control parameters were adjusted to prevent over-control.

3. Experiment

3.1 Japan Gigabit Network (JGN)

We used the Japan Gigabit Network (JGN) to evaluate the method's behavior in an actual large-scale network. The JGN was designed by the Telecommunications Advancement Organization (TAO) for research and development on very-high-speed networking and high-performance application technologies. It consists of nationwide, high-speed optical fibers with ATM switches. Access points provide access to researchers throughout Japan.

We implemented the dynamic load balancing method in the MPLS router (LSR) shown in Fig. 3 and built the MPLS network by setting up LSRs at four access points: the Makuhari Gigabit Research Center, the Kouchi Communication Traffic Research Center, the University of Tokyo, and the Kita-Kyushu Gigabit Laboratory (Fig. 4). These access points are interconnected with the ATM-CBR mesh topology (120 Mbps) through the JGN.

Fig. 3 MPLS router (LSR) with TE.

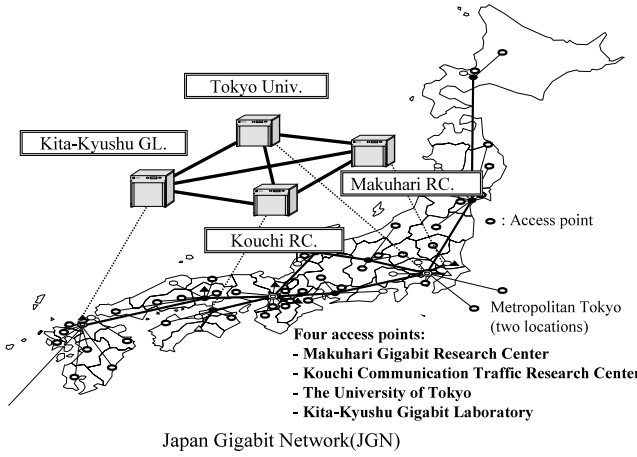
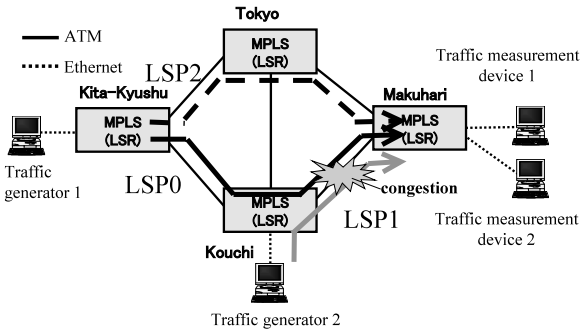


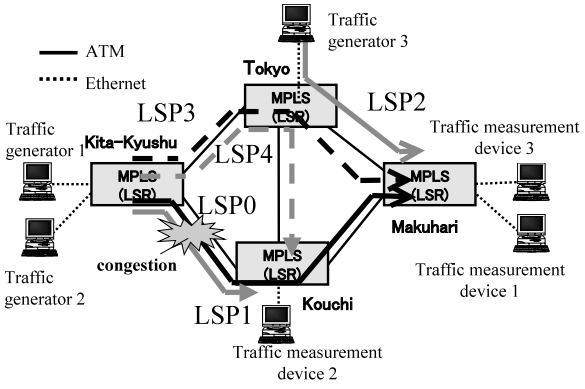
Fig. 4 MPLS network.

3.2 Network Models

We used two experimental models to evaluate the characteristics of the dynamic load balancing method—a simple network model of LSP traffic distribution and a complex model of the traffic distribution of multiple LSPs (Fig. 5). Using two models allowed us to determine whether the method's characteristics depend on the network model. In these experiments, only the LSR in Kita-Kyushu applied the load balancing method, so that we could verify the basic traffic behavior considered in Sect. 2.3 (i.e., the method was not applied at the other access points). We used measurement tools (Smartbit, Chariot) to generate a constant rate of traffic. To prevent the loss of transferred data because of network congestion, the network congestion threshold should be set low enough to prevent network congestion. In our experiments, to confirm the behavior of the load balancing through the default route (LSP0), we made the network congestion threshold value (40%: about 62 Mbps in the ATM layer) only slightly larger than the amount of LSP0's IP traffic (54 Mbps). The other environment and parameter values are given in Table 1. We sought to avoid network congestion within the first few minutes because there would be few rapid



(a) Network model 1.



(b) Network model 2.

Fig. 5 Network models.

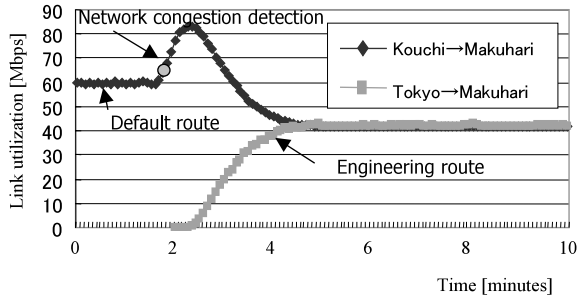
Table 1 Experimental environment & parameter values.

Item	Network model 1	Network model 2
The amount of IP traffic in the default route	LSP0: 54 Mbps (270 kbps: 200 flows) LSP1: 20 Mbps	LSP0: 54 Mbps (270 kbps: 200 flows) LSP1: 20 Mbps LSP2: 20 Mbps
Network congestion threshold	40% (about 62 Mbps)	40% (about 62 Mbps)
Flooding period	5 s	5 s

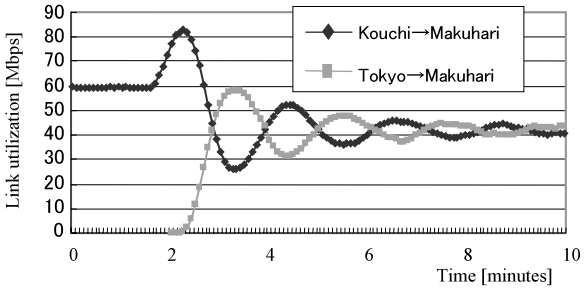
changes in the traffic of the backbone network. Further, in consideration of the LSR's processing performance, we set a flooding interval of 5 seconds.

Network Model 1: IP traffic was sent from Kita-Kyushu to Makuhari via Kouchi, and additional IP traffic was sent afterwards from Kouchi to Makuhari. When the LSR in Kita-Kyushu detected that the traffic between Kouchi and Makuhari had exceeded the network congestion threshold, it established an LSP on an engineering route from Kita-Kyushu to Makuhari via Tokyo.

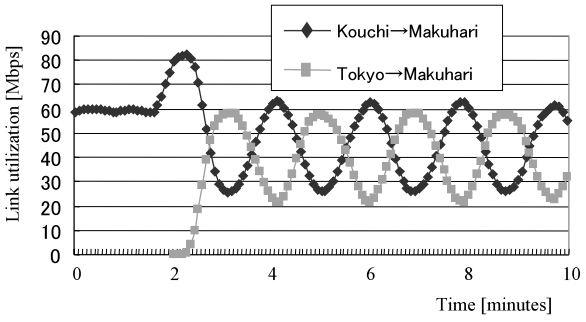
Network Model 2: IP traffic was sent from Kita-Kyushu to Makuhari via Kouchi, and additional IP traffic was sent at the same time from Kita-Kyushu to Kouchi and from Tokyo to Makuhari. When the LSR in Kita-Kyushu detected that the traffic between Kita-Kyushu and Kouchi had exceeded the network congestion threshold, it established an LSP on an engineering route from Kita-Kyushu to Makuhari via Tokyo and another LSP on an engineering route from Kita-Kyushu to Kouchi via Tokyo.



(a) Move Granularity: 10%.



(b) Move Granularity: 30%.



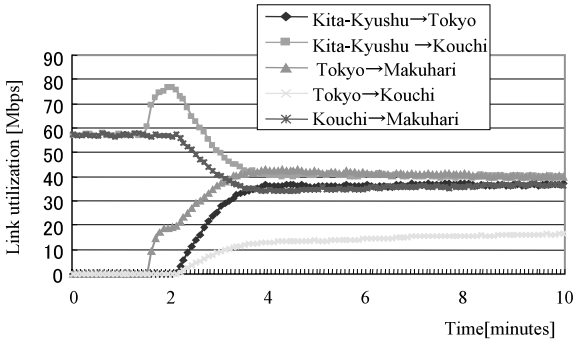
(c) Move Granularity: 50%.

Fig. 6 Experimental results (Network Model 1).

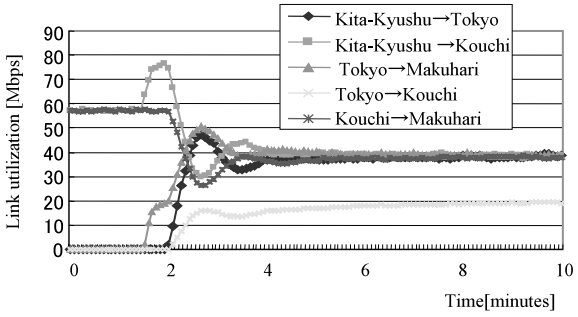
4. Results and Considerations

4.1 Characteristics Evaluation

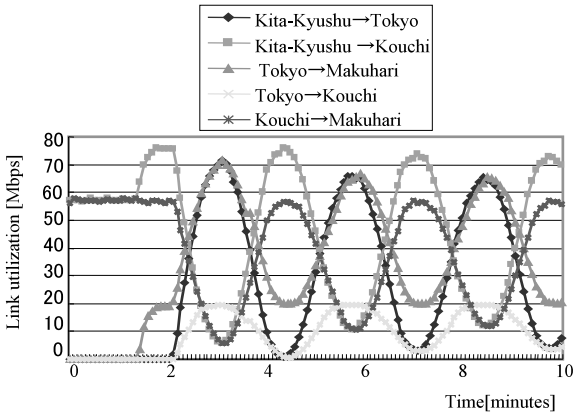
Figure 6 shows the link utilization vs. elapsed time in Network Model 1 for move granularity values of 10%, 30%, and 50%, with a smoothing factor of 5. The link utilization shows the amount of ATM layer traffic. As intended, the Kita-Kyushu LSR set up an LSP on an engineering route from Kita-Kyushu to Makuhari via Tokyo when the traffic between Makuhari and Kouchi increased (Fig. 6(a)), and the traffic between Makuhari and Tokyo increased rapidly as traffic was distributed to the engineering route. Ultimately, the link utilization between the default route and the engineering route was equalized. When the move granularity value was 30%, the link utilization was equalized while the traffic oscillation became smaller, but at 50%, the link utilization was not equalized and the traffic continued



(a) Smoothing factor: 1.



(b) Smoothing factor: 5.



(c) Smoothing factor: 10.

Fig. 7 Experimental results (Network Model 2).

to oscillate strongly.

The reason for this is that the IP flow distribution processing of the edge LSRs resulted in over-control, because a time lag had been created by the time the statistical information collected from each core LSR was reflected in the IP flow distribution processing of the edge LSRs. For example, the transmission delay between Makuhari and Kita-Kyushu in the JGN is over 10 ms. Therefore, when the move granularity was 10%, the traffic did not oscillate in moving a certain amount of traffic little by little. When traffic oscillates,data is transferred unstably in certain flows as a result of the traffic coming and going between the default route and the engineering route.

Figure 7 shows the link utilization vs. elapsed time in Network Model 2 for smoothing factors of 1, 5, and 10, with a move granularity of 30%. When the smoothing factor was 1, the link utilization was immediately equalized; when it was 5, the utilization was equalized while the traffic was still oscillating; but when the value was 10, the utilization was not equalized and the traffic continued to oscillate strongly. This is explained below.

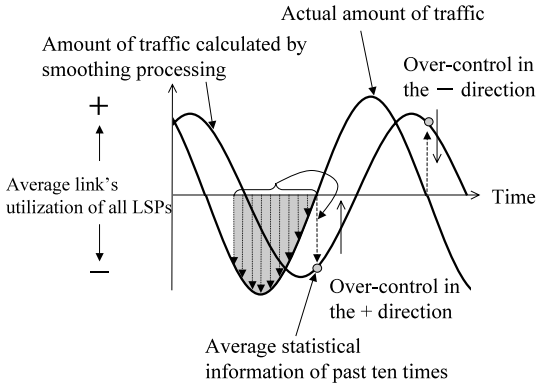


Fig. 8 Actual traffic vs. traffic calculated by smoothing processing.

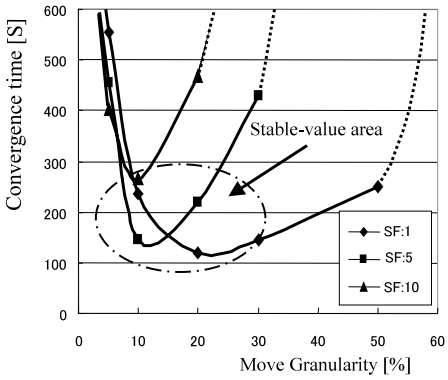
Figure 8 shows the relation between the actual amount of traffic and the amount of traffic calculated by smoothing the statistical information from the default route. (The latter value was obtained by averaging the 10 most recent statistical values.) The amplitude of the link utilization became smaller than the actual amount of traffic, and the phase shifted back. Therefore, even when traffic is actually equalized, the IP flow distribution processing results in over-control.

Thus, control parameters such as the move granularity and smoothing factor significantly affect the input flows and can result in unstable link utilization (oscillation). Because the link utilization must be equalized as quickly as possible, it is important to obtain appropriate parameter values to ensure the stability of the load balancing control.

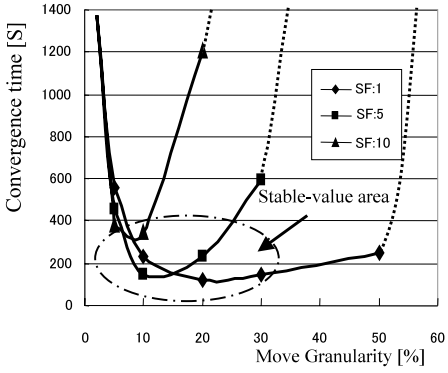
4.2 Network Stability

We define the convergence period, at the end of which traffic is equally distributed, as the time from when an edge LSR detects network congestion to the time when a difference of less than 1% is detected between the maximum utilizations of each link making up the default route and the engineering route. This period was measured to examine the relationship between the move granularity and the smoothing factor.

Figure 9 shows the relation between the move granularity and the convergence time in Network Models 1 and 2. When the move granularity was small, a fairly long time was needed to achieve stability because the amount of traffic was equalized gradually. When the move granularity value was large, it also took some time to achieve stability because the traffic was equalized while oscillation continued. The link utilization



(a) Network model 1.



(b) Network model 2.

Fig. 9 Relation between move granularity and convergence time.

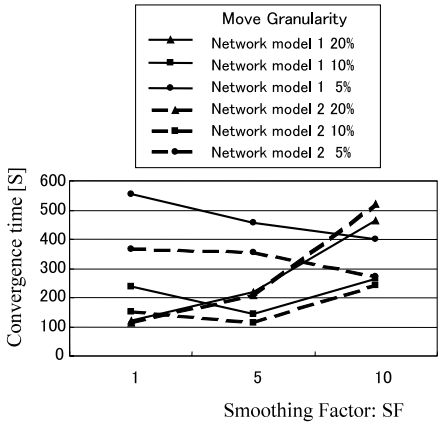


Fig. 10 Relation between smoothing factor and convergence time.

was not equalized under conditions of oscillation when the move granularity was within the area shown by the dashed line.

When the smoothing factor (SF) was large, the stable-value area was narrow for both network models because the traffic tended to oscillate. For the stable-value area, the move granularity was between 5% and 30%.

Figure 10 shows the relation between the smoothing factor and the convergence time. When the move granularity was 10%, the convergence time remained almost constant (i.e., within 300 seconds for both models), regardless of the smoothing factor. Thus, the move granularity appears to be the most important parameter for ensuring that traffic can be distributed equally. The effectiveness of the dynamic load balancing method can be appreciated when one considers that its use means that there will be few rapid changes in traffic when a backbone network is assumed as the target network.

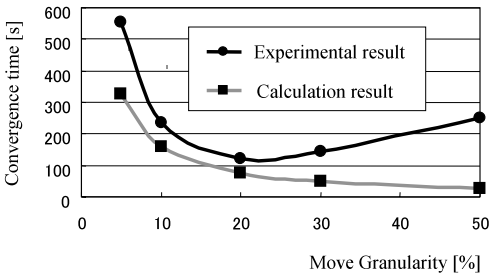


Fig. 11 Comparison of experimental and calculation results.

4.3 Comparison with the Calculated Results

To determine the influence of the time lag with respect to the transmission delay and the device processing time, we numerically analyzed a simple model in which the traffic collection processing of each LSR and the IP flow distribution processing of the edge LSRs were completely synchronized. For this model we used Network Model 1 with traffic distributed between two LSPs and a smoothing factor of 1.

We define move_traffic$_0$ as the amount of traffic movement that can be completely equalized through a single movement, move_traffic$_n$ as the amount of traffic that can be moved after n movements, and α as the move granularity, where move_traffic$_n$ is given by

$$\begin{aligned} \text{move\_traffic}_1 &= \text{move\_traffic}_0 \times (1-\alpha) \\ \text{move\_traffic}_2 &= \text{move\_traffic}_0 \times (1-\alpha)^2 \\ &\cdots\cdots\cdots \\ \text{move\_traffic}_n &= \text{move\_traffic}_0 \times (1-\alpha)^n. \end{aligned} \tag{2}$$

The value of n is obtained from

$$n = \frac{\log\left(\text{move\_traffic}_n / \text{ move\_traffic}_0\right)}{\log(1-\alpha)}. \tag{3}$$

The convergence time is obtained from the product $N \times F$. Here, N is the value of n at which move_traffic$_n$ becomes less than 1% of the link utilization, and F is the flooding interval. For Network Model 1, the relation between the move granularity and convergence time is shown in Fig. 11. The experimental and calculated results were closest to each other when the move granularity was between 10% and 20%. The results differ because the calculated results did not account

for the engineering route finding time, the set-up time, and so on. The difference increased greatly as the move granularity increased from about 20%. When the move granularity was larger than 20%, the edge LSRs caused over-control because of the time lag between the traffic collection processing and the IP flow distribution processing. This happened because the difference between the actual amount of traffic that should be moved and the amount of traffic that is extracted also grows as the move granularity increases.

5. Demonstration System

To confirm the method's effectiveness, we constructed a demonstration system and tested it by using input traffic from an actual digital cinema application.

As shown in Fig. 12, 80 Mbps of IP traffic from the digital cinema application was sent from Makuhari A's cinema server to Makuhari B's cinema client. Load IP traffic of 65 Mbps was added from Kouchi, and network congestion occurred between Makuhari B and Makuhari A. The amount of traffic between Makuhari B and Makuhari A was approximately 170 Mbps when the IP traffic was converted into an ATM cell rate. When the load balancing method was not applied, about 50 Mbps of ATM cells were discarded because the Virtual Path (VP) between the access points was an ATM CBR 120-Mbps path. If frames of a digital cinema application are dropped, this will noticeably degrade the application performance.

On the other hand, when our method was applied, the traffic from Kouchi was distributed to the engineering route via Kouchi, Tokyo, and Makuhari B, and we confirmed that none of the frames of the application were discarded. Here, the throughput improved to about 1.4 times the calculated value because it was possible to forward 170 Mbps of traffic by distributing it over two routes. Although only one example is described here, the improvement in the throughput rate will depend on the network topology (ring, mesh, etc.)

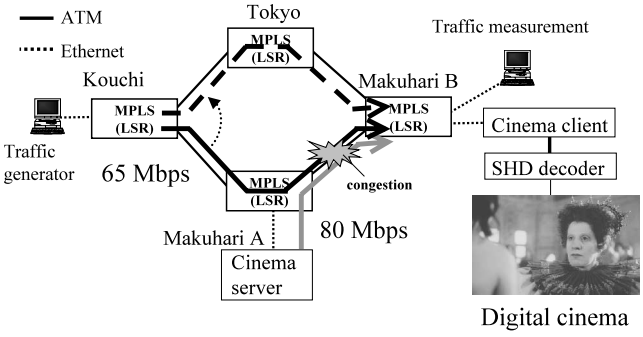


Fig. 12 Demonstration system using a digital cinema application.

6. Conclusion

An MPLS network with TE capability and four access points was constructed on the JGN, and we used this network to evaluate the characteristics of a dynamic load balancing method. In particular, we focused on the distributed processing problem that results in over-control due to the time lag with respect to the transmission delay in a large-scale network and the device processing time. Our results have demonstrated that this method provides stable load balancing control through changes made in the control parameter values. We confirmed that setting appropriate values enables traffic to be equally distributed over two or more routes in a large-scale real network. We verified the method's effectiveness by using a digital cinema application as input traffic.

In our continuing research, we will evaluate the characteristics of this method to prevent over-control due to the load balancing execution on multiple edge LSRs and the differences among various traffic types (constant and burst). In particular, we will focus on the smoothing factor under burst traffic in considering an access network and a metro network.

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