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Analysis of Network Traffic and its Application to Design of High–Speed Routers

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SUMMARY A rapid growth of the Internet and proliferation of new multimedia applications lead to demands of high speed and broadband network technologies. Routers are also necessary to follow up the growth of link bandwidths. From this reason, there have been many researches on high speed routers having switching capabilities. To have an expected effect, however, a control parameters set based on traffic characteristics are necessary. In this paper, we analyze the network traffic using the network traffic monitor and investigate the Internet traffic characteristics through a statistical analysis. We next show the application of our analytical results to parameter settings of high speed switching routers. Simulation results show that our approach makes highly utilized VC space and high performance in packet processing delay. We also show the effect of flow aggregation on MPLS. From our results, the flow aggregation has a great impact on the performance of MPLS.

key words: Internet, Traffic Measurement, Log Normal Distribution, Flow Aggregation, MPLS

1. Introduction

A rapid growth of the Internet and proliferation of new multimedia applications lead to demands of high speed and broadband network technologies. Accordingly, the capacity of the bandwidth has been increased rapidly. In Japan, for example, several ISPs (Internet Service Provider) increase the backbone bandwidth from 1.5 Mbps to 155 Mbps in last two years. A packet processing capability of routers are also necessary to follow up the growth of link bandwidths. From this reason, several techniques have been proposed for high speed routers. For example, IETF is now standardizing MPLS (Multi Protocol Label Switching) [1], which combines the flexibility of layer–3 routing with the high capacity of layer–2 switching. In MPLS, the router identifies a *flow* by IP addresses and applications (i.e., port numbers) of packets, and forwards them through faster switching paths.

However, its performance must be strongly affected by the control parameters set as well as hardware limitations of routers. To choose the appropriate control parameters set, we need to know the characteristics of the Internet traffic, by which we expect to obtain an expected performance of switching routers. For this purpose, we first investigate the characteristics of the actual Internet traffic using the traffic monitor called OC3MON developed by MCI [2]. Of course, the study on the characterization of the Internet traffic is not new. Traffic monitoring and its statistical analysis have already been studied in the literature [2]–[7]. Our main contribution in this paper is that we show that results of the statistical analysis are applied to determination of control parameters necessary in high speed switching routers.

When ATM is considered as a underlying network in MPLS, the MPLS router assigns the VC (virtual circuit) of ATM to each flow. However, due to the hardware specification of the ATM switch, the number of VCs are limited. Moreover, the performance of MPLS routers is measured by how many packets can be transmitted through hardware switching (i.e., VCs). From these reasons, MPLS switches are necessary to identify flows containing a large number of packets, which we will refer to as long–lived flows. In MPLS, two parameters are used to describe long–lived flows. The first parameter is the threshold value X; the MPLS switch monitors the number of packets for each flow, and determines the flow with X or more packets as a long–lived flow. The second parameter is a time–out value T. Because the MPLS switch cannot detect the end of flow, the switch has to decide that the flow is finished when the packet does not arrive on the assigned VC during T seconds.

The number of packets in the flow depends on the parameter set (X, T) and it is impossible to consider two parameters X and T independently. In Section 3, we will demonstrate how our statistical analysis can be utilized for determining those two papramaters in order to obtain high performance MPLS routers. Since the traffic load (the arrival rate of flows) at the routers is time–varying as we observed in our traced data. We will also show the adaptive control method to determine the control parameters of MPLS routers according to the traffic load.

One technique to effective utilize VC space is a flow aggregation, in which flows are aggregated into one flow with a larger granularity of classification (e.g., from port number to IP address). Aggregated flows have a larger number of packets and a longer flow duration. These properties give a significant impact on the performance of MPLS switches [7]. In this paper, we will first show that the aggregated flow has a same statistical distribution, which means that our analytic formulas can be applied to aggregated flows. Then, the effect of flow aggregation is demonstrated using the simulation technique.

In this paper, we first give analytical results of the network traffic, which are gathered by the traffic monitor OC3MON at our university. Our approach and results are summarized in Section 2. We then proceed to investigate the application to high speed IP switching techniques in Section 3. Section 4 shows the effect of flow aggregation. Finally, we conclude our work with future research topics in

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Section 5.

2. Analysis of Traced Data

In this section, we analyze traced data collected by the traffic monitor. Note again that there are many studies about traffic measurement and its statistical analysis. Our main contribution is to consider how to apply our results of the statistical analysis to determination of control parameters necessary in high speed switching routers. For this purpose, we first give our analytical results. The application to high speed router is shown in the next section.

2.1 Analysis Approach

In this subsection, we introduce our analytic approach. We follow the statistical approach described in Paxson's previous work [4] where the approach was applied to the analysis of `telnet` and `ftp` traffics. The analysis of WWW traffic analyzed by the same approach [5]. In the approach, we first choose several probability distributions, and determine parameters of those distribution functions based on traced data. In this paper, we have adopted following distributions in addtion to an exponential distribution, an extreme distribution, a normal distribution. We consider a log–normal distribution and a log–extreme distribution. If the random variable $Y = \log X$ has a normal (extreme) distribution, then X is said to have a log–normal (log–extreme) distribution. Namely, log–normal and log–extreme distributions are defined as

$$F(x) = \int_0^x \frac{1}{\sqrt{2\pi}\sigma y} exp\left[\frac{-(\log y - \zeta)^2}{2\sigma^2}\right] dy, \quad (1)$$

and

$$F(x) = exp\left[-exp\left(-\frac{\log x - \alpha}{\beta}\right)\right]. \quad (2)$$

Those distributions were taken into account since they can cover a large range of values. We also consider a Pareto distribution which is defined as

$$F(x) = 1 - \left(\frac{k}{x}\right)^{\alpha}, \quad x \geqq k, \quad (3)$$

Note that it is often used for modeling the self–similar traffics [6], [8].

We then test the goodness–of–fit of each model to select the most appropriate distribution via chi–squared examination. We use a criterion $\hat{\lambda}^2$ to choose the best model from the above–mentioned probability distributions. The criterion $\hat{\lambda}^2$ of each model is derived as follows. Suppose that we have observed n instances of random variables. We partition the range of those instance into N bins. Each bin has a probability p_i which is the proportion of the distribution falling into the ith bin. Let Y_i be the number of observation falling into the ith bin. Then $\hat{\lambda}^2$ is defined as

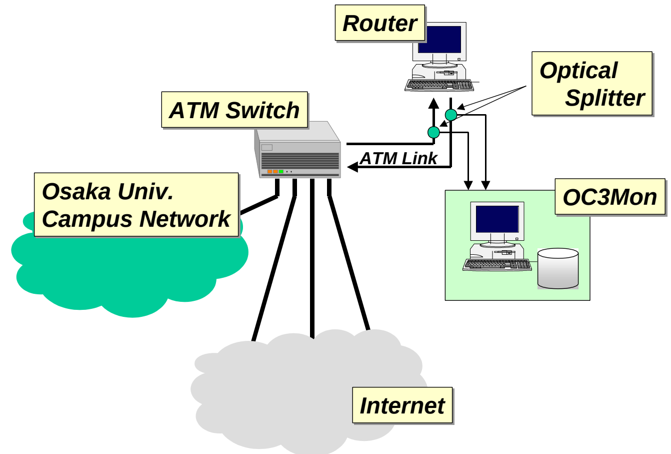

Fig. 1 Configuration of OC3MON

$$\hat{\lambda}^2 = \frac{X^2 - K - N + 1}{n - 1}, \quad (4)$$

where

$$X^2 = \sum_{i=1}^{N} \frac{(Y_i - np_i)^2}{np_i}, \qquad K = \sum_{i=1}^{N} \frac{Y_i - np_i}{np_i}. \quad (5)$$

Finally, we choose the distribution with the smallest value of $\hat{\lambda}^2$ as a most accurate one.

2.2 Analytical Results

In this subsection, we give analytical results of the network traffic, which are gathered by the traffic monitor OC3MON. The monitor is placed at the gateway of Osaka University (see Figure 1), i.e., our results reflect the characteristics of the traffic between the Internet backbone and the large–scale local network.

Summary of the traced data collected by OC3MON is shown in Table 1. We monitored the gateway during a one day. Note that traced data is divided into four parts due to its file volume in Table 1. As shown in Table 1, the number of packets was 81,767,103 and the total transmission size was about 43.1 GBytes. Table 2 summarizes several statistics dependent on the application. We identified the packet stream having the same source address, destination address and application (port number) as an individual *flow*. As shown in the table, the ratio of HTTP traffic is very high and the volume of major three applications (HTTP, FTP, and NNTP) becomes over 80% of all traffic in bytes. It coincides recent trends of the network traffic reported in the literature [2], [3]. We can also see the statistical difference among applications. For example, the flow of FTP contains 15 packets in average while the DNS flow does only two packets.

Based on the analysis approach described in the previous subsections, we now present the statistical results.

- The distribution of IP address access frequencies

Table 1 Summary of Traced Data

No	Time	Duration (hours)	# of Packets	Transmission in MBytes
1	99.2.2 17:45	6	22,077,118	10,581
2	99.2.3 0:35	8	9,182,052	4,703
4	99.2.3 9:20	4	23,303,624	11,169
3	99.2.3 13:30	6	26,574,308	12,737

Table 2 Statistics Dependent on Applications (ratio)

appli-cation	# of pkts.	# of bytes (Mbytes)	# of flows
HTTP	40,440,520 (49.5%)	20,336 (51.9%)	4,067,691 (63.1%)
FTP data	11,361,570 (13.9%)	8,830 (22.5%)	59,641 (0.9%)
NNTP	12,080,756 (14.8%)	6,166 (15.7%)	67,269 (1.0%)
DNS	2,839,998 (3.5%)	394.4 (0.9%)	1,212,246 (18.8%)
SMTP	2,322,079 (2.8%)	541.2 (1.4%)	155,068 (2.4%)
FTP	611,559 (0.7%)	61.3 (0.2%)	33,968 (0.5%)
TELNET	1,010,214 (1.2%)	91.2 (0.2%)	50,895 (0.8%)
POP3	559,684 (0.7%)	119.6 (0.3%)	27,139 (0.4%)
others	10,540,732 (12.9%)	2,694 (6.9%)	770,370 (12.0%)

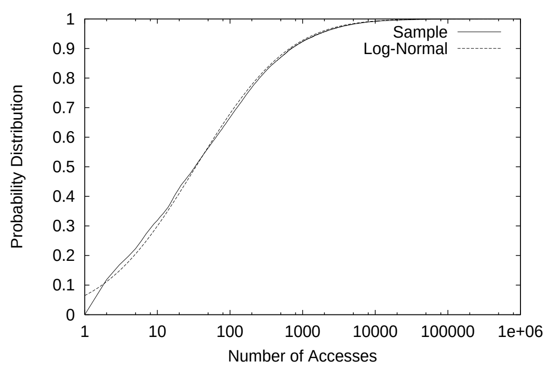

Fig. 2 The Distribution of Access Frequencies of IP Addresses

The distribution of access frequencies of IP addresses is shown in Figure 2. The best model was a log–normal distribution. We can observe that the most of addresses are accessed at least twice, and that most frequently accessed WWW sites have more than 10,000 accesses.

- The distribution of the number of packets within the flow

  We next show the analytic results of the distribution of the number of packets contained in each flow. Figure 3 shows the result. The best one was a log–normal distribution which has a long–tail.

  However, if we focus on the tail of the distribution,

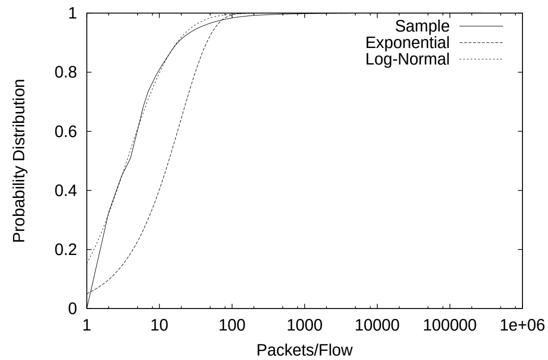

Fig. 3 Distribution of the Number of Packets in Flows

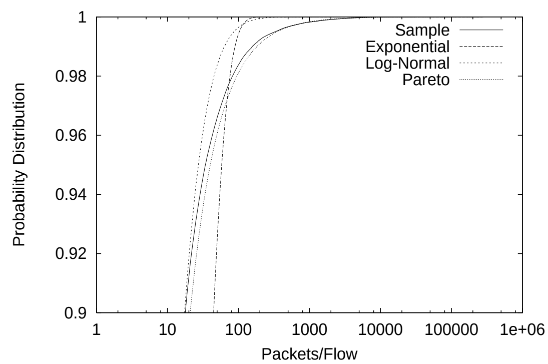

Fig. 4 Distribution of the Number of Packets in Flows (Tail Part)

  the log–normal distribution cannot follow the traced lines [6]. Figure 4 shows the tail part of the distribution. As shown in the figure, a more suitable model is the Pareto distribution, which is known as a class of the heavy–tailed distribution decaying very slowly in its tail. It coincides recent studies on the traffic characterization on the Internet. However, we should note that the heavy-tailed distribution well fits only in its tail. If we consider the entire distribution, the log–normal distribution is best. Henceforth, we will consider the log–normal distribution for parameterizing the traffic flow in the next section.

- The distribution of flow duration

  The best model of the distribution of flow durations is also a log–normal distribution for the entire distribution, and a Pareto distribution for the tail. That is, the characteristics are same as the distribution of the number of packets in the flow described above. We omit the result due to space limitation.

- The distribution of flow intervals

  We finally show the inter-arrival distributions of flows in Figure 5. The best model is an exponential distribution. That is, we can assume that the flow arrivals follows a Poisson distribution.

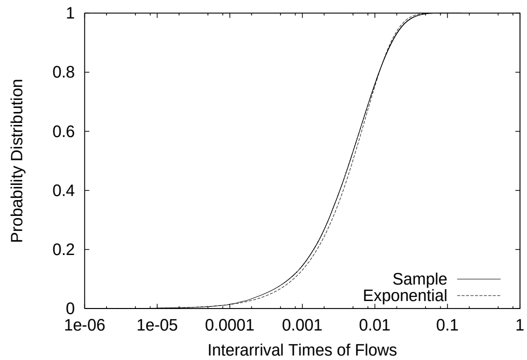

Fig. 5 Distribution of Flow Inter-arrival Times

3. Application to High Speed IP Switching

In this section we investigate the application of analytical results to determination of control parameters necessary in high speed switching routers. One important example is MPLS applied to ATM. In MPLS, the VC (virtual circuit) setting is activated by the predefined number X of packets contained in the flow, and it is released by the timeout value T. More specifically, when the number X of packets from the same flow are processed by the MPLS switch, the flow is recognized to need to set up VC so that the faster hardware switching is performed. The assigned VC is released when the switch does not receive any packets of the flow within T seconds. Thus, the performance of MPLS is affected by the parameters X and T, which depends on the traffic characteristics of flows. If the parameter X is small, many VC assignments would be required not only for long–lived flows (which includes the large number of packets in the flow) but also for short–term flows, which results in the failure of setting more VCs for the long–lived flows newly arriving at the switch. On the other hand, if the parameter X is large, the utilization of VC space becomes low, and the switch performance is degraded. Moreover, the larger value of the parameter T leads to lower utilization of VC spaces while the switch with the small parameter T releases a VC of an active flow. Effects of a parameter set (X, T) in MPLS have been studied [9], [10], but those studies did not take account of traffic characteristics.

One difficult and unavoidable problem in determining appropriate values of X and T lie in that MPLS switch cannot isolate the flow if two or more consecutive flows have identical IP address and the port number. The timeout value T is then used to identify the flows. That is, the number of packets in the flow depends on the parameter T, and it is impossible to consider two parameters X and T independently. It is possible to obtain the appropriate value of T for each parameter X. However, it requires large computation time, and is not suitable for on–line calculations. In this section, we first demonstrate that the parameter X is a key for the switch performance. After that, the determination method of parameters X and T based on our statistical analysis. The effect of the parameter T is also discussed.

3.1 The Preliminary Results

While we have two parameters X and T for MPLS, we only consider X in this subsection to demonstrate that the parameter X plays an important role to achieve the high performance MPLS switch. In doing so, we assume that the switch can identify the end of the flow so that it immediately releases the VC setting at the end of flow. Of course, in the actual situation, it is not impossible from source/destination IP addresses and port numbers, unless the switch monitors, e.g., the "FIN" segment in the case of TCP. We will discuss the effect of the parameter T in the next subsection.

To determine the appropriate parameter X, we introduce the following notations. Let $F(x)$ be the distribution function of the number of packets in flows (i.e., log–normal distribution according to our analysis) given by

$$F(x) = \int_0^x \frac{1}{\sqrt{2\pi}\sigma y} exp\left[\frac{-(\log y - \zeta)^2}{2\sigma^2}\right] dy. \qquad (6)$$

Furthermore, $E_U(X)$ represents the mean number of packets of flows which contain less than X packets, and the mean processing time of the packet by "software" is denoted as δ. Similarly, $E_L(X)$ is the mean number of packets of flows having larger than or equal to X packets, and γ shows the packet processing delays in "hardware" switching.

We then have a mean flow processing time, Y, as

$$\begin{aligned} Y &= F(X)\delta E_U(X) \\ &\quad + (1 - F(X))\{\delta X + \gamma(E_L(X) - X)\}, \end{aligned} \qquad (7)$$

Equation (7) shows that the router can process $1/Y$ flows in unit time. To process all flows without any packet losses, Y is required to satisfy $Y < 1/\lambda$ where λ is an arriving rate of flows. We then determine the value of X based on hardware specifications. From our traced data, we found that $X = 6$ was most appropriate. However, such a "static approach" does not take account of the fluctuation of the traffic load. The adaptive control method is thus necessary to effectively utilize the line capacity dependent on the traffic load. The approach of our adaptive control is next described.

We first introduce the time interval t_a. For each t_a, the switch observes the traffic load (the number of newly arriving flows), and changes the threshold value $X(t)$ adaptively. Then, we expect that the number of assigned VCs for every t_a is around the target value B. The target value B may be set by the static result, i.e.,

$$B = V_{max} - \lambda t_a(1 - F(X)). \qquad (8)$$

We then determine the next $X(t + t_a)$ by balancing in and out flows for time interval t_a. For this, we introduce $V_d(t)$ as the variation caused by changing the parameter $X(t)$. We define $V_d(t)$ as

$$\begin{aligned} V_d(t) &= t_a\lambda'(t)(1 - 2F(X(t_1)) + F(X(t))) \\ &\quad - V(t)R(t_a), \end{aligned} \qquad (9)$$

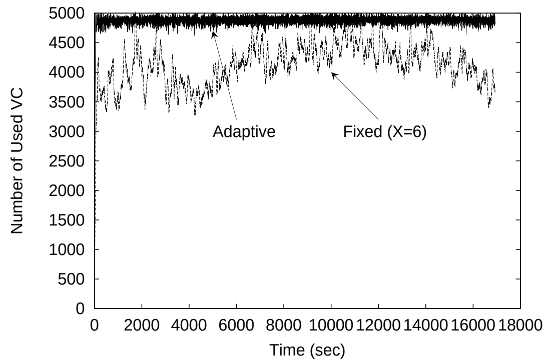

Fig. 6 Comparison of the Numbers of Assigned VCs Dependent on Time

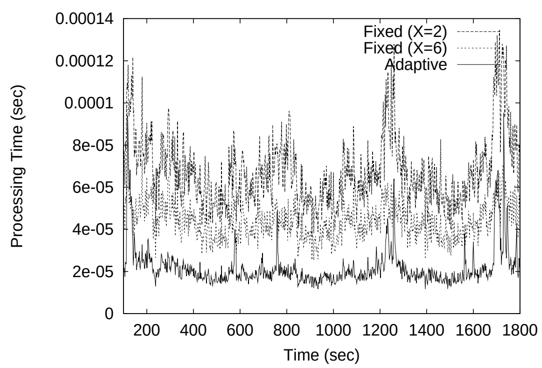

Fig. 7 Comparison of Mean Packet Processing Times Dependent on Time

where $R(t_a)$ gives the ratio of the long–lived flows which ceases its connection within t_a. It is derived from the residual time for given distribution, i.e.,

$$R(t_a) = \frac{1}{\mu} \int^{t_a} (1 - F(X(t)))dt, \tag{10}$$

Then, the adequate threshold value for next t_a is determined by taking account of $V_d(t)$. That is, we calculate the smallest value of $X(t + t_a)$ satisfying

$$V_d(t) \leqq B - V(X(t)). \tag{11}$$

Figure 6 shows the results of trace–drive simulation to compare the static and adaptive control methods. In simulation, the maximum number of VCs, V_{max}, is set to be 5000, and t_a is 2 sec. In the adaptive control, we set $B = 4,900$. As can be seen in the figure, VCs are highly utilized and its usage is stable around the threshold $B = 4,900$. Figure 7 shows the comparison of the mean packet processing times dependent on time. As shown in this figure, the benefit of highly utilized VCs leads to reduction of the packet processing time (83 μsec to 22 μsec).

3.2 Determination of Two Control Parameters

As having been demonstrated in the previous subsection, the parameter X is a key for the switch performance. However, we have to consider the parameter T in addition to the parameter X. As having been described before, the duration of the flow observed by the switch is affected by the parameter T.

Before describing the determination method, we first see its influence. For this purpose, we again analyzed the flow duration and the number of packets within the flow from the traced data by varying the value of T. Note that the parameter X is assumed to be fixed at 5 during the experiments. Through the analysis, we confirmed that both of the flow duration and the number of packets within flows follow the log–normal distributions while the parameters of distributions depend on the parameter T. We also observed that the arrival process of flows follow the Poisson distribution.

Let S_T represent the random variable of the flow duration for given T. Since each flow holds the VC during $S_T + T$ and flows arrive according to the Poisson distribution, we may view the MPLS router as an $M/G/1/\infty$ queue by assuming that VCs are provided sufficiently. The steady–state probability p_j of our $M/G/\infty$ queue is obtained by

$$p_j = e^{-\lambda(E(S_T)+T)} \frac{\{\lambda(E(S_T) + T)\}^j}{j!}. \tag{12}$$

When the router can assign the number N_{VC} of VCs, the probability that VC assignment fails is approximately given by

$$L_{VC} = 1 - \sum_{j=0}^{N_{VC}} p_j. \tag{13}$$

and the average number of simultaneously assigned VCs, $\overline{N_{VC}}$, is given by

$$\overline{N_{VC}} = \sum_{j=1}^{N_{VC}} jp_j/(1 - L_{VC}). \tag{14}$$

From equation (13), we can calculate the minimum number of N_{VC} which is necessary to satisfy that L_{VC} is, e.g., less than 1%. Figure 8 shows such an example. In the figure, the relation between the parameter T and the minimum/average numbers of simultaneously assigned VCs. In plotting the figure, we set the parameter $X = 5$. From this figure, the number of VCs increases almost in proportion to the timeout value T. For instance, the appropriate value of T was 28 (sec) if the router has 5,000 VCs.

Remaining is that we need to know the statistics for various values of X, by which we can change the control parameters of MPLS routers according to the traffic load fluctuation. For this purpose, we first need to investigate the number of required VCs dependent on the parameter X (and T). We can determine it by examining the traced data for

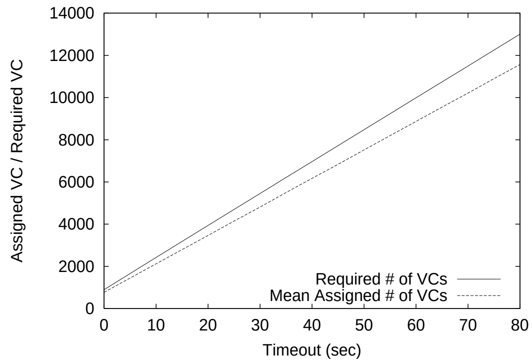

Fig. 8 The Number of Simultaneously Assigned VCs ($X = 5$)

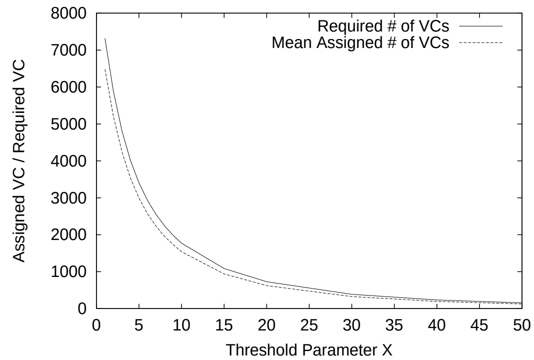

Fig. 9 Relation between X and # of Assigned VCs

all possible values of X. However, it is apparently a time–consuming approach, and fortunately we also confirmed that the flow duration and the number of packets within the flow have a strong correlation.

We first consider the case of $X = 1$; i.e., the router assigns VCs to all flows. In this case, analytic results can be used directly. That is, the required number of VCs, N_{VC_1}, and the average number of VCs, $\overline{N_{VC_1}}$, are determined from equations (13) and (14).

For $X > 1$, VC assignment is performed when the Xth packet of the flow arrives at the router. The distribution of the holding time of the assigned VC $S(y)$ is given as

$$S(y) = \begin{cases} 0, & y < Z(X-1) \\ \frac{G(y-Z(X-1))}{(1-F(X))}, & \text{otherwise} \end{cases} \quad (15)$$

where $F(x)$ and $G(y)$ are distributions of the number of packet in flows and the flow duration, respectively. Note that both follow the log–normal distributions according to our statistical analysis. Z is mean packet inter–arrivals of flows.

The arrival rate of flows λ_X for given X is

$$\lambda_X = (1 - F(X))\lambda \quad (16)$$

since VC is assigned only when the flow has a number X or more packets. By applying $S(y)$ and λ_X to an $M/G/\infty$ queue as in the previous subsection, we can determine the minimum number of VCs, N_{VC_X}, and the average number of VCs, $\overline{N_{VC_X}}$, from equations (13) and (14).

Finally, the processing load of the router, which is defined as ρ_{VC}, can be derived as

$$\rho_{VC} = \gamma\overline{N_{VC_X}} + \delta(\overline{N_{VC_1}} - \overline{N_{VC_X}}). \quad (17)$$

where the mean processing time of the packet by software is denoted as δ, and γ shows the packet processing delays in hardware switching.

Figure 9 shows the effect of the parameter X on the number of required VCs. In this case, we set T = 28 sec, $\gamma = 250$ μsec, $\delta = 10\mu$sec. As shown in this figure, $X = 3$ is an appropriate value when the VC space is 5,000. Figure 10 shows the effect of the parameter X on the processing load of the router. From this figure, $X \leqq 6$ is necessary

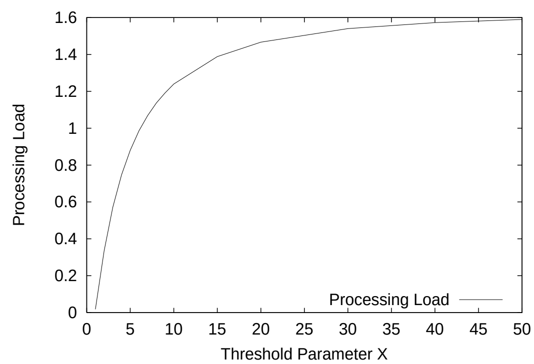

Fig. 10 The Processing Load of the Router Dependent on X

in order to be able to process all packets completely (i.e., $\rho_{VC} \leqq 1$). This result coincides with the observation made in the previous subsection.

We finally show the effect of the parameter tunings in Figure 11. In the figure, we plot two cases of the timeout values; T = 60 sec and T = 30 sec. The parameter X was determined by the above equations. The VC space was set to be 5,000. As shown in the figure, we can observe that the mean packet processing time is decreased by tuning parameters, which leads to the performance improvement of the switching capacity of the router. We last note that since our formulation allows time–dependent arrival rate of flows (see equation (16)), the control parameters can be adaptive to the traffic load if the appropriate traffic load monitoring is performed.

4. Effects of Flow Aggregation

So far, we assume that flows are identified by {*source host IP address, destination host IP address, source host port number, destination host port number*}. However, it is likely that the switching performance can be improved by flow aggregation, by which we mean that flows having the same destination port is treated by a single flow. As a result, it is expected that the router can assign VCs to more flows.

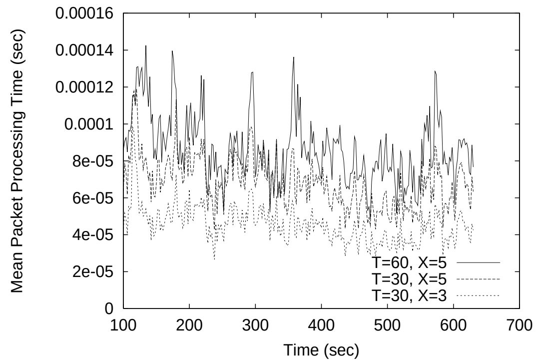

Fig. 11 Effect of Tuning of Parameters X and T

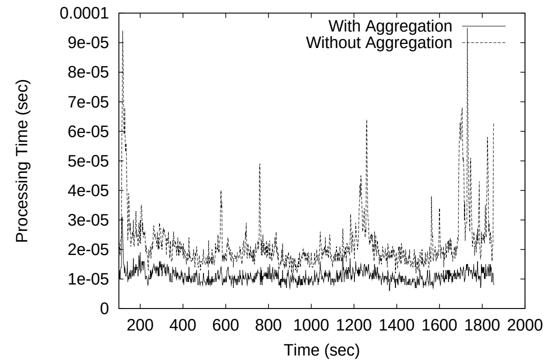

Fig. 12 Effect of Flow Aggregation on Packet Processing Delays

Table 3 Result of Analysis of Aggregated Flows

Distribution	Distribution	Ratio
# of packets in the flow	log–normal	1.301
(Tail Part)	Pareto	
Flow duration	log–normal	1.096
(Tail Part)	Pareto	
Inter-arrivals of flows	log–normal	0.861
(Tail Part)	Pareto	

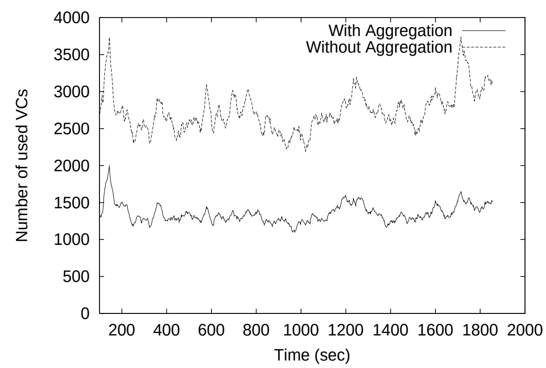

Fig. 13 Effect of Flow Aggregation on the Reuired Number of VCs

Such a performance improvement can be clearly expected when we consider the HTTP/1.0 protocol. Namely, when the WWW browser retrieves one HTML file and several in–line images, only one VC is required to transmit those files by the flow aggregation. Even when HTTP/1.1 is employed, an inappropriate setting of the timeout value T is likely to lead to the failure of performance improvement. It is because the MPLS router tends to treat the HTTP connection as multiple flows if the small value of the timeout T is selected.

In this subsection, we identify flows with three values

$\{$*source host IP address, destination host IP address, destination host port number (application)*$\}$

to aggregate flows, and show its effect on the performance of MPLS routers.

We first summarize the characteristics of aggregated flows in Table 3. The third column of the table (labeled by "Ratio") shows the ratio of aggregated flows to non–aggregated flows. For example, the average number of packets in aggregated flows is 1.301 times larger than the one in non–aggregated flows. From the table, it can be observed that durations of flows with and without aggregations are close. It is because flow durations include the timeout value (T = 28 sec in the current case). If we exclude timeouts, the ratio becomes 1.75. Another observation in this table is that all of statistics have the same distributions. Namely, we can apply our previous analysis to the case of aggregated flows.

To investigate the effect of flow aggregation on MPLS routers, trace–driven simulation was performed. Results on the mean packet processing time and the number of assigned VCs are shown in Figures 12 and 13, respectively. We determined the parameter X from Section 3.1. The number of simultaneously assigned VCs becomes drastically degraded (almost half) by flow aggregation. As a result, the mean packet processing delay becomes small and the router can assign VCs to more flows.

5. Concluding Remarks

In this paper, we first give analytical results of the network traffic which are gathered by the traffic monitor. Through the statistical analysis, we found that most statistics, including the number of packets in the flow and active flow durations, follow the log–normal distributions. We next investigate the application to parameter settings in high speed MPLS routers. From simulation results, VCs are able to be highly utilized and its usage is stable by applying the result of analysis for parameter settings. We also show the effect of flow aggregation. Simulation results show a clear performance improvement on number of used VCs.

In this paper, we have not considered somce QoS levels dependent on applications. However, QoS level must be different among application, and therefore, the treatement of flows should be differentiated at the MPLS routers. For future research topics, it is necessary to consider some mechanism to application–dependent flow identification and VC setting.

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