Performance analysis of IP datagram transmission delay in MPLS: 
Impact of both the number and the bandwidth of LSPs on Layer 2

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Abstract — LSR (Label Switching Router) in MPLS (Multi-Protocol Label Switching) networks map arriving IP flows into some labels on Layer 2 switching fabric and establish LSP (Label Switching Path)s. By using LSPs, LSRs not only transmit IP datagrams fast with cut-through mechanism, but also solve traffic engineering issue to optimize the delay of some IP datagram flows. So far, we have analyzed the performance of LSR focusing only on the maximum number of LSPs which can be set on Layer 2. In this paper, we will also consider the bandwidth allocated to each LSP and analyze the IP datagram transmission delay and the cut-through rate of LSR. We suppose the label mapping method as the data-driven scheme in the analytical model, so that the physical bandwidth of LSR is shared by both the default LSP for hop-by-hop transmission and the cut-through LSPs. Thus, we will investigate the impact of the bandwidth allocation among these LSPs on the performance.

I. INTRODUCTION

As the Internet continues to grow exponentially, the number of users is increasing explosively. There is also increasing demand for the multimedia applications in real-time, which require quite stringent quality of service (QoS) delivery on packet loss rate and minimum bandwidth.

However, the conventional IP router may be a bottleneck in terms of high-speed data transfer, since it carries out forwarding decisions in software based on address resolution with hop-by-hop transmission of IP datagrams of variable length. Then, MPLS (MultiProtocol Label Switching) is proposed as the technique for improving transmission delay by the hardware switching in Layer 2 [1].

LSR (Label Switching Router) in MPLS network is employed to combine Layer 3 routing with Layer 2 high-speed switching efficiently and transfer IP datagrams fast by cut-through transmission via LSP (Label Switched Path)s on Layer 2. Moreover, it can treat the traffic engineering issue by setting up various type of LSPs. It has been implemented in Ipsilon’s (that is currently Nokia’s) "IP switch[5]." Toshiba’s "CSR (Cell Switch Router)[6]." Cisco’s "Tag Switching[7]" and IBM’s "ARIS (Aggregated Route-Based IP Switching)[8]" so far.

To establish LSPs, LSR has to map arriving IP flows into some labels on Layer 2 such as VCI (Virtual Channel Identifier) of ATM switch. This label mapping method is mainly divided into two schemes. One is the data-driven scheme and the other is the control-driven one[2].

So far, we have analyzed the performance of LSR focusing only on the maximum number of LSPs which can be set on Layer 2 in case of the data-driven scheme [3], and compared it with that of the control-driven scheme [4]. In both papers, we neglected the bandwidth of each LSP and investigated only the queueing delay on the Layer 3 routing kernel. In this paper, we will also consider the bandwidth of each LSP and derive the transmission delay on Layer 2 and the processing delay on LSR. In the analytical model, we assume the label mapping method as the data-driven scheme, in which IP flows up to the maximum number of LSPs are transmitted by cut-through, but exceeded flows are raised to the routing kernel and transmitted by the default LSP which is preestablished for hop-by-hop transmission.

Therefore, the bandwidth allocation of LSR among the default LSP and cut through LSPs will become important in improving delay performance. Hence in this paper, we will investigate the impact of the bandwidth allocation of LSR as well as the amount of incoming traffic on the performance.

This paper is organized as follows. Section II describes the mechanism and the analytical model of LSR. Section III analyzes the steady state probability of LSR and derive some performance measures. Section IV provides numerical results and examines the impacts of some parameters on performance. Finally, Section V gives a brief conclusion and future works.

II. ANALYTICAL MODEL OF LSR

A. LABEL SWITCHING ROUTER: CUT-THROUGH MECHANISM

Figure 1 illustrates the concept of LSR. LSR consists of Layer 2 switching fabric and Layer 3 routing kernel. Here, we assume Layer 2 switching fabric as ATM switch.

The LSR is connected with both upstream and downstream nodes by ATM physical circuits whose bandwidth is $f$[Mbps]. In the data-driven scheme, if the first datagram in some IP flow, which is classified by source-destination IP addresses and/or port numbers, arrives at LSR, it is mapped into the specific label, i.e., VCI (Virtual Channel Identifier) and the VC is established as cut-through LSP between the corresponding upstream and downstream nodes.
When the bandwidth for cut-through transmission is set to $B_{\text{cut}}[\text{Mbps}]$ and $n_{\text{vc}}(1 \leq n_{\text{vc}} \leq N_{\text{vc}})$ VCs are used, the bandwidth of each cut-through VC becomes $B_{\text{cut}}/n_{\text{vc}}[\text{Mbps}]$, where $N_{\text{vc}}$ is the maximum number of VCs which can be set on the ATM switch. If $N_{\text{vc}}$ VCs are used and new IP flow arrives, datagrams in the flow cannot be cut-through and they are raised to the routing kernel of Layer 3 and hop-by-hop transmitted. Thus the default VC has to be preestablished via the routing kernel and its bandwidth is set to $B_{\text{def}} = B - B_{\text{cut}}[\text{Mbps}]$.

B. Source Model Description

In this paper, we assume that data flows into LSR are User datagram Protocol (UDP) used as a transmitting protocol of many real-time applications, and that IP datagram length is fixed. Thus, we consider a discrete-time queueing system.

Therefore, we adopt the Bernoulli process as traffic model in which datagram arrives with probability $\lambda_D$ per slot. When the number of sources multiplexed in LSR is set to $N$, probability $P_i$ that $i$ datagrams reach LSR simultaneously in a slot is expressed as follows.

$$P_i \triangleq \binom{N}{i} \lambda_D^i (1 - \lambda_D)^{N-i}.$$  \hspace{1cm} (1)

Therefore, average total arrival rate of IP datagrams $\lambda$ in LSR is given by

$$\lambda = N \lambda_D.$$ \hspace{1cm} (2)

C. Analytical Queueing Model

In this analysis, the physical bandwidth of LSR is shared by both the default VC for hop-by-hop transmission and the cut-through VCs. Here, we let probability $\mu_{\text{def}}$ and $\mu_{\text{cut}}$ denote as

$$\mu_{\text{def}} = \frac{B_{\text{def}}}{B}, \quad \mu_{\text{cut}} = \frac{B_{\text{cut}}}{B},$$ \hspace{1cm} (3)

namely, in some slot, the datagram assigned on cut-through VCs is transmitted with prob. $\mu_{\text{cut}}$ while one stored in the routing kernel is with prob. $\mu_{\text{def}}$.

The analytical model of LSR is shown in Fig.2. A processing part of Layer 2 can be expressed by the virtual queue in which the buffer size is $N_{\text{vc}}$ and the service rate is $\mu_{\text{cut}}$ in a slot. Therefore, it is modeled by the batch geometric/1/$K(=N_{\text{vc}})$ queue with the arrival rate $\lambda$ and the batch size $N$. Here, we do not suppose the buffering on Layer 2 ATM switch.

When the LSR uses all cut through VCs, newly arriving datagrams are raised to the Layer 3 routing kernel. Therefore, if the buffer size is infinite, the Layer 3 can be expressed by the batch geometric/1 queue with the service rate $\mu_{\text{def}}$.

III. Analysis of LSR Model

A. Random Variable of System

Since the datagrams not assigned on any cut-through VCs are processed on Layer 3, we cannot analyze each queue of Layer 2 and Layer 3 separately. Therefore, we need to evaluate simultaneously both the queue lengths of the routing kernel, and cut-through VCs in use as states in the queueing system.

Here, we define following random variables in the $t$th slot.

- $D(t)$ : the queue length in datagrams of the buffer at the routing kernel ;
- $S(t)$ : the number of cut-through VCs under transmission processing in Layer 2 ATM switch.

Since sources are homogeneous in terms of traffic characteristics, we can completely describe the state of our system by the above variables. Furthermore, each source generates datagrams according to Bernoulli process described in the previous section, so that the system state $\{D(t), S(t); t = 0, 1, 2, \cdots\}$ can form a discrete time Markov chain.

B. Datagram arrival probability at routing kernel

Here, we denote the random variable $a(t)$ that represents the number of the datagrams stored in the routing kernel at the $t$th slot. There are two cases representing the situation that the state $S$ changes from $i$ to $j$ and $x$ datagrams arrive at the routing kernel in some slot.

- When the datagram in some cut-through LSPs is served, $x$ datagrams are stored in the routing kernel;
- On the other hand, when the datagram in the routing kernel is served, $x$ datagrams are stored in it.

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*Performance analysis of IP datagram transmission delay in MPLS by S. Nakazawa et al.*
In the former case, since LSR processes one datagram of \( i \) cut-through VCs, LSR can accommodate up to \( N_{\text{VC}} - i + 1 \) datagrams on cut-through VCs and more datagrams are lifted up to the routing kernel. If \( i = 0 \), i.e., no cut-through VC is used, up to \( N_{\text{VC}} \) datagrams can be held on Layer 2.

Therefore, we define datagram arrival probability in the former case as \( a_{i,j}^{(2)}(x) \) and obtain it as follows:

\[
a_{i,j}^{(2)}(x) \triangleq \Pr\{a(t) = x, S(t) = j|S(t-1) = i\}
\]

when the datagram in some LSPs is served at \( t \)th slot

\[
= \begin{cases} 
  P_{i} & \text{if } i = 0, j < N_{\text{VC}}, x = 0 \\
  P_{i-1} & \text{if } i > 0, i-1 \leq j < N_{\text{VC}}, x = 0 \\
  P_{i,N_{\text{VC}}+i} & \text{if } i > 0, j = N_{\text{VC}} \\
  0 & \text{otherwise}.
\end{cases}
\] (4)

Similarly, we can obtain datagram arrival probability \( a_{i,j}^{(3)}(x) \) in the latter case as follows:

\[
a_{i,j}^{(3)}(x) \triangleq \Pr\{a(t) = x, S(t) = j|S(t-1) = i\}
\]

when the datagram in the routing kernel is served at \( t \)th slot

\[
= \begin{cases} 
  P_{i-j} & \text{if } i \leq j < N_{\text{VC}}, x = 0 \\
  P_{N_{\text{VC}}-i,x} & \text{if } j = N_{\text{VC}} \\
  0 & \text{otherwise}.
\end{cases}
\] (5)

As mentioned above, we can show the transition probability matrix \( A_{2}(x), A_{3}(x) \) representing that the datagram on Layer 2 and Layer 3 is transmitted, respectively, and \( x \) datagrams arrive at routing kernel with changing state of utilized cut-through VCs on Layer 2 as follows.

\[
A_{k}(x) = \begin{pmatrix} 
  a_{0,0}^{(k)}(x) & \cdots & a_{0,j}^{(k)}(x) & \cdots & a_{0,N_{\text{VC}}}^{(k)}(x) \\
  \vdots & \ddots & \vdots & \ddots & \vdots \\
  a_{i,0}^{(k)}(x) & \cdots & a_{i,j}^{(k)}(x) & \cdots & a_{i,N}^{(k)}(x) \\
  \vdots & \ddots & \vdots & \ddots & \vdots \\
  a_{N_{\text{VC}},0}^{(k)}(x) & \cdots & a_{N_{\text{VC}},j}^{(k)}(x) & \cdots & a_{N_{\text{VC}},N_{\text{VC}}}^{(k)}(x)
\end{pmatrix}
\] (6)

for \( k = 2, 3 \).

C. Steady state probability

We define the system state probability at the \( t \)th slot as

\[
P_{i}(b, i) \triangleq \Pr\{D(t) = b, S(t) = i\},
\] (7)

and the steady state probability \( x(b, i) \) and its vector representation as

\[
x(b, i) \triangleq \lim_{t \to \infty} P_{i}(b, i),
\]

\[
x_{b} = [x(b, 0), \ldots, x(b, i), \ldots, x(b, N_{\text{VC}})].
\] (8)

Since the system state forms Markov chain of \( M/G/1 \) type queueing system, \( x_{b} \) can be related to the transition probability matrix \( A_{2}(x) \) and \( A_{3}(x) \) as follows [9]:

\[
x_{b} = x_{0}B(b) + \sum_{i=1}^{\infty} x_{i}A(b+1-i), \quad b \geq 0
\] (9)

\[
\sum_{b=0}^{\infty} x_{b}e = 1,
\]

where \( e \) is a column vector of ones and \( A(x) \) and \( B(x) \) are given by

\[
A(i) = \mu_{\text{def}}A_{3}(i) + \mu_{\text{cut}}A_{2}(i-1),
\]

\[
B(i) = A_{2}(i).
\] (10)

Furthermore, Eq.(9) can be stably solved by using the algorithm proposed in [10].

D. Derivation of performance measures

By using the steady state probability obtained in the previous subsection, we can get following performance.

1) Cut-through rate, \( R_{c} \): We will first derive the cut-through rate \( R_{c} \). \( R_{c} \) is the ratio of the average number of datagrams transmitted by cut-through to that of datagrams generated from whole sources when the maximum number of cut-through VC is set to \( N_{\text{VC}} \). This is given by

\[
R_{c} = \frac{1}{\lambda_{\text{def}}} \sum_{i=0}^{\infty} \left( x(b, 0) \sum_{i=1}^{N_{\text{VC}}} \min(k, N_{\text{VC}})P_{k} + \sum_{i=1}^{N_{\text{VC}}} x(b, i) \times \sum_{k=1}^{N} (\mu_{\text{def}} \min(k, N_{\text{VC}}-i) + \mu_{\text{cut}} \min(k, N_{\text{VC}}-i+1)) P_{k} \right).
\] (11)

2) Average datagram processing delay, \( W_{p} \): There are two cases of datagram transmission in LSR. One is hop-by-hop transmission of datagram via Layer 3 routing kernel and the other is cut-through one by cut-through VC.

First, we can derive the average datagram waiting time in case that datagrams are stored in the routing kernel by the following formula.

\[
W_{\text{def}} = \frac{1}{\lambda_{(1-R_{c})}} \sum_{i=1}^{\infty} x(b, i).
\] (12)

Next, we can derive the average datagram transmission delay if datagrams are transmitted by cut-through VC as follows.

\[
W_{\text{cut}} = \frac{1}{\lambda R_{c}} \sum_{i=0}^{\infty} x(b, i).
\] (13)

Therefore, we will obtain the average datagram processing delay in LSR as follows.

\[
W = (1-R_{c})W_{\text{def}} + R_{c}W_{\text{cut}}.
\] (14)
IV. NUMERICAL RESULTS AND DISCUSSIONS

In this section, we first investigate the behavior of $R_c$, $W_{\text{def}}$, $W_{\text{cut}}$ and $W$ as a function of $N_{\text{vc}}$, then discuss the impact of bandwidth allocation between $B_{\text{def}}$ and $B_{\text{cut}}$ on the performance, where $B_{\text{def}}$ is the bandwidth for the default VC and $B_{\text{cut}}$ is for cut-through VCs.

Throughout this section, we set the number $N$ of sources to 20, the physical bandwidth of LSR, $B$, to 150[Mbps], and IP datagram length to 400[bytes].

A. Comparison of Simulation Results and Impact of $N_{\text{vc}}$

As mentioned in Sec.II.B, the bandwidth of each cut-through VC becomes $B_{\text{cut}}/n_{\text{vc}}$, where $n_{\text{vc}}(1 \leq n_{\text{vc}} \leq N_{\text{vc}})$ is the number of cut-through VC in use. However, we approximately modeled the processing part of Layer 2 as the virtual queue whose buffer size is $N_{\text{vc}}$ and the transmission bandwidth is set to $B_{\text{cut}}$. Therefore, we simulate the above exact model to verify the accuracy of our analytical model.

Figure 3 compares the simulation result with that obtained by the analysis. We set the bandwidth, $B_{\text{def}}$: $B_{\text{cut}}$, to 20:130[Mbps] and the total traffic $\lambda$ to 0.9. From this figure, we can say that the analysis in which the processing part of Layer 2 can be modeled very well by the batch discrete time

gem/D/1/K queue. Therefore, from now on, we will only show performance measures obtained by the analysis.

From Fig.3(a), the cut-through rate $R_c$ increases as $N_{\text{vc}}$ monotonously. In terms of delay from Fig.3(b), if $N_{\text{vc}}$ gets large, the transmission delay $W_{\text{cut}}$ by cut-through is increasing whereas the queueing delay $W_{\text{def}}$ in routing kernel is drastically decreasing. The reason is that the number of datagrams transmitted by cut-through increases as $N_{\text{vc}}$. On the other hand, the bandwidth of each cut-through VC becomes small if $N_{\text{vc}}$ is large so that $W_{\text{cut}}$ becomes large. Therefore, the average processing delay $W$ in LSR can take the minimum value; e.g., at $N_{\text{vc}}=7$ in Fig.3(b).

B. Impact of bandwidth $B_{\text{def}}$: $B_{\text{cut}}$

In this subsection, we investigate the impact of the bandwidth $B_{\text{def}}$: $B_{\text{cut}}$ on the performance. We set $B_{\text{def}}$: $B_{\text{cut}}$ to 5:145, 20:130, 75:75, 100:50, and 120:30[Mbps] and represent it as "B$_d$:B$_c$" in figures.

Figure 4(a) shows $R_c$ when the total traffic $\lambda$ is 0.9. Although $R_c$ is increasing as $N_{\text{vc}}$, it gets saturated if $N_{\text{vc}}$ is set to a large value and the saturated value of $R_c$ becomes $B_{\text{cut}}/B\lambda$ (if the value exceeds 1, it approaches to 1 as $N_{\text{vc}}$ increases).

Figs.4(b) and (c) show $W_{\text{def}}$ and $W_{\text{cut}}$. As $B_{\text{cut}}$ is increasing, $W_{\text{cut}}$ decreases while $W_{\text{def}}$ exponentially increases. Moreover, the number of $N_{\text{vc}}$ at which $W_{\text{def}}$ becomes some fixed value also becomes large. Therefore, as shown in Fig.4(d), the value of $N_{\text{vc}}$ minimizing the processing delay $W$ in LSR depends on $B_{\text{def}}$: $B_{\text{cut}}$. We will define this optimum value as $N_{\text{vc}}^*$ and show $N_{\text{vc}}^*$, $W$ and $W_{\text{def}}$: $W_{\text{cut}}$ of Table 1. $W_{\text{def}}$: $W_{\text{cut}}$ seems to represent the effectiveness of the cut-through transmission. From the table, $N_{\text{vc}}^*$ increases as $B_{\text{cut}}$ whereas $W$ gets almost same value. Nevertheless, $W_{\text{def}}$: $W_{\text{cut}}$ is increasing.

V. CONCLUDING REMARKS

So far, we have analyzed the performance of LSR focusing only on the maximum number of LSPs which can be set on Layer 2. In addition, in this paper, we have also considered the bandwidth of each LSP and analyze the IP datagram transmission delay and the cut-through rate of LSR. We ap-

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Table 1. Impact $B_{\text{cut}}$ on $W_{\text{def}}$: $W_{\text{cut}}$

<table>
<thead>
<tr>
<th>$B_{\text{cut}}$[Mbps]</th>
<th>$N_{\text{vc}}^*$</th>
<th>$W$[msec]</th>
<th>$W_{\text{def}}$: $W_{\text{cut}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>30</td>
<td>2</td>
<td>0.136</td>
<td>0.58</td>
</tr>
<tr>
<td>50</td>
<td>2</td>
<td>0.142</td>
<td>1.32</td>
</tr>
<tr>
<td>75</td>
<td>3</td>
<td>0.157</td>
<td>1.88</td>
</tr>
<tr>
<td>100</td>
<td>4</td>
<td>0.172</td>
<td>3.25</td>
</tr>
<tr>
<td>130</td>
<td>7</td>
<td>0.197</td>
<td>7.79</td>
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<tr>
<td>145</td>
<td>19</td>
<td>0.188</td>
<td>20.1</td>
</tr>
</tbody>
</table>
approximately modeled the part of Layer 2 as one virtual queue and the numerical results obtained from the analysis agree with that of simulation very well.

Through some numerical results, we have obtained the followings.

- The cut-through rate $R_c$ will approach some value if $N_{VC}$ is large and the value becomes $B_{cut}/B\lambda$ (if the value exceeds 1, it approaches 1 as $N_{VC}$ increases).
- LSR has the optimum number $N_{VC}^*$ of cut-through VC which minimizes its processing delay $W$ in LSR. Both $N_{VC}^*$ and $W_{def}/W_{cut}$ when $N_{VC}$ equals $N_{VC}^*$ increase as $B_{cut}$.

We analyzed the performance of LSR in this research focusing on UDP used as a transmitting protocol of the real-time application. Furthermore, we will need to consider the priority control of LSR which also multiplexes non-real-time traffic.

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