A Simple Estimation Scheme for Upper Bound of Link Utilization Based on RTT Measurement

Kiyofumi Igai and Eiji Oki

***Abstract*—This paper proposes a scheme based on Round-Trip Time (RTT) measurement to estimate the upper bound of link utilization. In conventional active measurement schemes, probe packets are temporarily transmitted at greater than the available bandwidth through the link under test to estimate its utilization rate. This degrades the quality of communication for existing traffic passing through the link. In the proposed scheme, two RTTs are measured from a source host to both end nodes of a targeted link to obtain their probability distribution functions; the bandwidth used by the probe packets is much smaller than that available. The link utilization rate is estimated by deconvoluting the measured RTT values. Numerical results show that the proposed scheme estimates link utilization with an accuracy of 13% under bursty traffic while not degrading existing traffic and follows time-varying link utilization on the second time scale.**

***Index Terms*—link utilization, round-trip time, probability distribution function, convolution, time-varying.**

I. Introduction

LINK utilization is a key metric in detecting if a network is congested, or judge if link capacity is sufficient to ensure that the of communication quality meets the customer's requirements. Using link utilization, the network operators control communication to keep communication quality. To realize high-accuracy of communication control, the operators have to estimate link utilization with frequency or constantly. Link utilization is defined as the ratio of used bandwidth to link capacity. Network tomography is to obtain network performance by measuring. There are two approaches to estimating link utilization: passive and active.

The passive measurement approach does not transmit any probe packet, so traffic passing though the link is not affected by the measurement. Traffic information is directly collected at each node on the link by using, for example, the Simple Network Management Protocol (SNMP) [1]. This approach measures the link utilization in an accurate manner and frequently or constantly measures it. However, it is not always possible to get the information due to administrative restrictions.

Manuscript received July 26, 2011.

This work was supported in part by the Strategic Information and Communications R&D Promotion Programme of the Ministry of Internal Affairs and Communications, Japan.

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In the active measurement approach, the network performance is estimated by sending probe packets from a source host to another node on the targeted path. The active measurement approach includes Train Of Packet Pair (TOPP) , Self Loading Periodic Stream (SLoPS) schemes, Network Radar. [2] – [11]. TOPP sends sequence packet pairs on the path at increasing rates [2], [5], [6], [7]. Based on the relationship between the input and output rates of different packet pairs, the observer can estimate the available bandwidth of a bottleneck link, which has the smallest available bandwidth on a path. In SLoPS, a source host sends periodic streams over the path at several constant rates [3], [4], [8]. If the rate is higher than the available bandwidth, the one-way delay variation of received packets show increasing trend. Otherwise the one-way delay variation doesn't show increasing trend. The available bandwidth of the bottleneck link is estimated by analyzing the trend. The advantage of the active measurement approach is that an observer can estimate link utilization without accessing each node. In other words, it does not face any administrative restriction. However, both the TOPP method and SLoPS send probing packets are sent over the path, at rates temporarily greater than the available bandwidth. This causes overloaded. Because of overloaded, it is not feasible that this scheme frequently or constantly measures the link utilization.

Another network tomography technique was presented as Network Radar [10], [11]. This scheme measures RTT to obtain packet loss variance and delay variance on a shared link. An observer analyzes these variances to estimate the network performance. The advantage of this scheme is that sending probe packets does not cause any overload because the probe packet can be set to small. However, the purpose of this scheme is not to estimate link utilization but to estimate loss variance and delay variance on the shared link.

A link utilization estimation scheme based on RTT measurement was psresented [9]. This scheme measures two RTTs from a source host to both end nodes of a targeted link to obtain their probability distribution functions. The link utilization rate is estimated by deconvoluting the measured RTT values. The advantage of this scheme is that sending probe packets does not cause any overload because the probe packet can be set to small. However, traffic model for evaluation is too simple in [9].

This paper proposes a scheme based on Round-Trip Time (RTT) measurement that can accurately estimate the upper bound of link utilization. In the proposed scheme, two RTTs are measured from a source host to both end nodes of a targeted link to obtain their probability distribution functions; the bandwidth used by the probe packets is much smaller than that available. Link utilization is estimated by deconvoluting the measured values. A simulation shows that the proposed scheme estimates link utilization with 13% accuracy under bursty traffic, while not affecting existing traffic and follows alteration of link utilization on the second time scale.

The remainder of this paper is organized as follows. Section II shows the details of the proposed scheme. Section III presents performance evaluations of the proposed scheme. The work is concluded on Section IV.

II. Proposed Scheme

A. Link Utilization

When a packet passes through a node, it is delayed. The one-way delay from a node to the next node on the link under test (LuT) consists of fixed and variable components, see Figure 1. Delay $D(i)$ for packet *i* is expressed by,

$$D(i) = T_f + T_q(i). \quad (1)$$

T_f includes fixed delays for forwarding and switching, serialization/de-serialization, and propagation. T_f is a constant value, which is independent of *i*, as long as the route of each packet is not changed. $T_q(i)$ is caused by queueing at the ingress node, where a packet has to wait before being transmitted to the output port.

Link utilization is estimated by using the delay probability distribution for LuT from the ingress node to the next node; note that the queuing delay at the neighbor node is not included. Queuing delay is measured if probe packets are sent from the ingress to the neighbor hop node through the link. When the queue at the ingress node is empty, there is no queueing delay, i.e.,$T_q(i) = 0$. In this case, the observer measures the minimum delay, which is defined as $D_{min} = \min_i D(i)$. If the observer focuses on the instantaneous time where $T_q(i) = 0$, the link is not utilized. On the other hand, if the queue is not empty, the delay for a packet passing through the link is varied by queueing. The observer measures a delay that is larger than D_{min}, where ($T_q > 0$). At this moment, the link is utilized. Let $p(x)$ be the probability distribution function with

$$x = D(i) - D_{min}. \quad (2)$$

Note that *x* is used in the same definition through this paper, unless stated otherwise.

The link utilization, which is denoted as *U*, is the probability that the queue is occupied by at least one packet, in other words, $x > 0$. Let the number of probe packets whose delay is D_{min} be $N_{x=0}$, and the number of probe packets whose delay is larger than D_{min} be $N_{x>0}$. *U* is obtained by,

$$U = 1 - p(0) = 1 - \frac{N_{x=0}}{N_{x>0} + N_{x=0}}. \quad (3)$$

B. Network Models

To estimate the link utilization expressed in Eq.(3), the proposed scheme measures the RTTs of many probe packets, as shown in Figure 2, instead of measuring one-way delay. This is because the measurement of one-way delay requires the strict time and clock synchronization of the two nodes. In general, queueing occurs at both ingress and egress nodes, as shown in Figure 2. The network model of Figure 2, employs the ping mechanism as specified in the Internet Control Message Protocol (ICMP) [13].

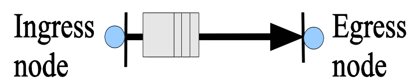

Fig. 1 Network model for one-way delay.

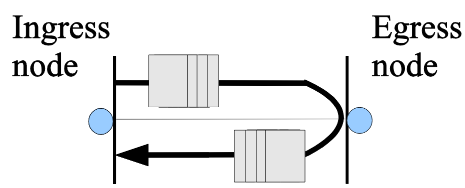

Fig. 2. Network models for RTT.

C. Procedure

The procedure of the proposed scheme consists of three steps, which are the measurement of RTT, the estimation of the probability distribution function, and the estimation of link utilization.

RTT Measurement

An observer at the source host measures the RTTs to both end nodes of the LuT. An observer measures RTTs from the source host to both end nodes at the same time and measures enough RTT-data to obtain the functions. The probability distribution functions of RTT from a source host to both end nodes are obtained from the RTTs.

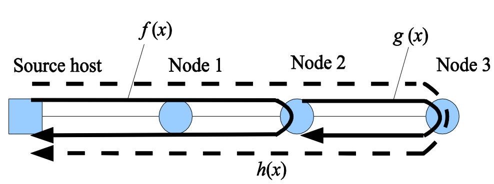

Fig. 3. Various RTTs on the path

As shown Figure 3, the observer obtains $f(x)$ and $h(x)$ as the probability distribution functions of RTTs from a source host to node 2 and node 3, respectively $g(x)$ is the probability distribution function of RTT, *x*, from node 2 (ingress node), to node 3 (egress node), of the LuT, where $g(x)$ can be not measured directly . $g(0)$ is the probability that the RTT from the ingress node to the egress node on the LuT takes the minimum delay.

Estimation of probability distribution function

$g(x)$ is estimated by deconvoluting $f(x)$ and $h(x)$ that are directly measured. As many TCP flows are accommodated on a link in a backbone network, it is assumed that traffic probabilistic behaviors for different links are independent. Therefore, $h(x)$ is the convolution of $f(x)$ and $g(x)$, where $h(0)$ is expressed by

$$h(0) = f(0)g(0). \quad (4)$$

By using Eq. (4), $g(0)$, which is not directly measurable, is obtained by,

$$g(0) = \frac{h(0)}{f(0)} \quad (f(0) \neq 0). \quad (5)$$

Estimation of probability distribution function

The observer is able to estimate the link utilization by using $g(0)$. Let $p(x)$ and $q(x)$ be the probability distribution functions of the one-way delay in the forward and backward directions, respectively (Figure 4). $g(0)$ is given by $p(0)$ and $q(0)$,

$$g(0) = p(0)q(0). \quad (6)$$

Because of queueing delay in the backward direction, $q(0) \leq 1$. So, $g(0) \leq p(0)$. By using Eq. (3) and $g(0) \leq p(0)$, the upper bound of U is obtained as,

$$U \leq 1 - g(0). \quad (7)$$

If there is no queueing delay in the backward direction, $q(0) = 1$. Thus, $g(0) = p(0)$.

By using Eq. (3) and $g(0) = p(0)$, U is obtained by,

$$U = 1 - g(0). \quad (8)$$

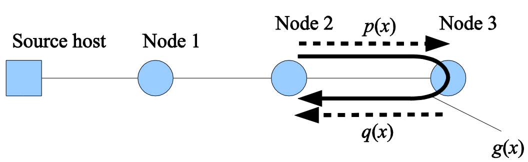

Fig. 4. OWDs and RTT on the LuT

III. EVALUATION

The proposed scheme is evaluated via computer simulations conducted using ns-3 [15]. Figures 5, 6, 7 and 8 show the network used in the simulation. The simulation conditions are as follows. The bandwidth of all links is set to 1 [Gbit/s], and the propagation delay of all links is 1 [ms]. Cross traffic, as shown in Figures 5, 6, 7 and 8 is randomly generated in each link to emulate the background traffic for each link. In this simulation, backward traffic is not set to evaluate the basic characteristics of the proposed scheme, so that link utilization can be specified by Eq. (8)

We evaluated the estimation accuracy of link utilization and dependency of deviations on measurement time on the network as Figures 5 and 6. And evaluated following variation of link utilization on the network as Figures 7 and 8.

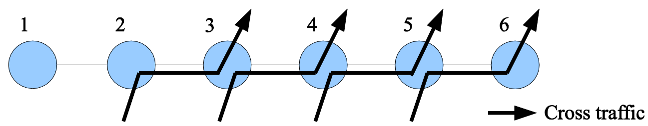

Fig. 5. Network 1 for case 1

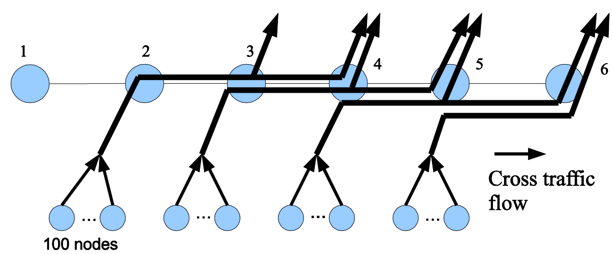

Fig. 6. Network 1 for case 2

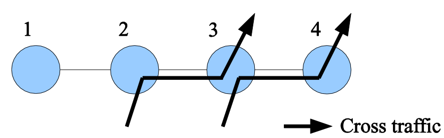

Fig. 7. Network 2 for traffic patterns 1 and 2

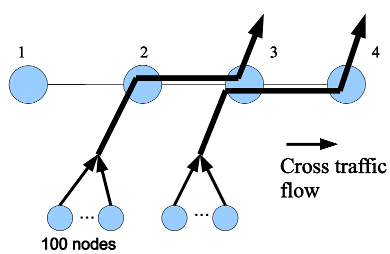

Fig. 8. Network 2 for traffic pattern 3

A. *Estimation accuracy of link utilization*

Case1

In Figure 5, among the four links through which cross traffic passes, one link is set to be the bottleneck, the one with the smallest available bandwidth on the path, and was set to traffic loads of 0.5, 0.7, or 0.9. The others are set to be non-bottleneck with fixed load of 0.3. Load is ratio of the link capacity to traffic rate. The size of request and reply packet is set to 32 [byte]. The packet sizes of cross traffic is set to 1200 [bytes]. Sending interval of request packets is set to 10 [ms]. Let U_{est} and U_{act} be the link utilization estimated by the proposed scheme and the actual link utilization, respectively. The deviation between U_{est} and U_{act}, Δ is defined by,

$$\Delta = | U_{est} - U_{act}|. \quad (9)$$

The deviations for each bottleneck link are shown in Tables I, II, and III, where the measurement time is set to 1000 [sec]. Average of Δ is under 0.03 and standard deviation is 0.016. Also, Δ does not at worst, exceed 0.08. This result shows that the proposed scheme estimates link utilization with an accuracy of 10%.

Case2

In Figure 6 among the four links through which cross traffic passes, one link is set to be the bottleneck, the one with the smallest available bandwidth on the path, and was set to traffic loads of 0.5, 0.7, or 0.9. The others are set to be non-bottleneck with fixed load of 0.3. The size of request and reply packet is set to 32 [byte]. Sending interval of request packets is set to 10 [ms]. 100 traffic sources were created. Cross traffic was generated from each sources and joined at the each link. 10% of joined cross traffic flows traverse the node. The cross-traffic packet sizes are distributed as follows: 1200 [bytes] are 30%, 800 [bytes] are 10%, and 500 [bytes] are 60% [14].

The deviations for each bottleneck link are shown in Tables IV, V and VI, where the measurement time is set to 1000 [sec]. Average of Δ is about 0.10 and standard deviation is 0.07. This result shows that the proposed scheme estimates link utilization with an accuracy of 10%.

B. *Dependency of deviation on measurement time and sending interval of probe packets*

The dependency of the deviation on the measurement time and sending interval of probe packets is also investigated. Δ_{avg} is defined as the average value of Δ during the period over all bottleneck links. Figure 9 shows that Δ_{avg} is smaller than 0.03 over a 10 second measurement period when the sending interval of probe packets is 1 [ms]. Δ_{avg} is smaller than 0.03 over a 80 second measurement period when the sending interval is 10 [ms]. This result shows that reducing the sending interval of probe packets reduces Δ for short time measurement periods.

Table I. Δ on each link when the link between nodes 3 and 4 is the bottleneck link under case 1.

	Load on bottleneck link		
Load	0.5	0.7	0.9
2-3	0.021	0.006	0.006
3-4	0.030	0.024	0.018
4-5	0.017	0.080	0.025
5-6	0.016	0.046	0.026

Table II. Δ on each link when the link between nodes 4 and 5 is the bottleneck link under case 1.

	Load on bottleneck link		
Load	0.5	0.7	0.9
2-3	0.012	0.012	0.007
3-4	0.048	0.049	0.053
4-5	0.015	0.017	0.015
5-6	0.016	0.013	0.013

Table III. Δ on each link when the link between nodes 5 and 6 is the bottleneck link under case 1.

	Load on bottleneck link		
Load	0.5	0.7	0.9
2-3	0.025	0.025	0.025
3-4	0.045	0.045	0.040
4-5	0.015	0.021	0.021
5-6	0.005	0.015	0.017

Table IV. Δ on each link when the link between nodes 3 and 4 is the bottleneck link under case 2.

	Load on bottleneck link		
Load	0.5	0.7	0.9
2-3	0.245	0.059	0.081
3-4	0.155	0.038	0.146
4-5	0.196	0.122	0.147
5-6	0.089	0.099	0.046

Table V. Δ on each link when the link between nodes 4 and 5 is the bottleneck link under case 2.

	Load on bottleneck link		
Load	0.5	0.7	0.9
2-3	0.014	0.103	0.229
3-4	0.013	0.004	0.186
4-5	0.151	0.158	0.136
5-6	0.131	0.039	0.023

Table VI. Δ on each link when the link between nodes 5 and 6 is the bottleneck link under case 2.

	Load on bottleneck link		
Load	0.5	0.7	0.9
2-3	0.218	0.022	0.060
3-4	0.030	0.116	0.221
4-5	0.099	0.249	0.049
5-6	0.066	0.078	0.168

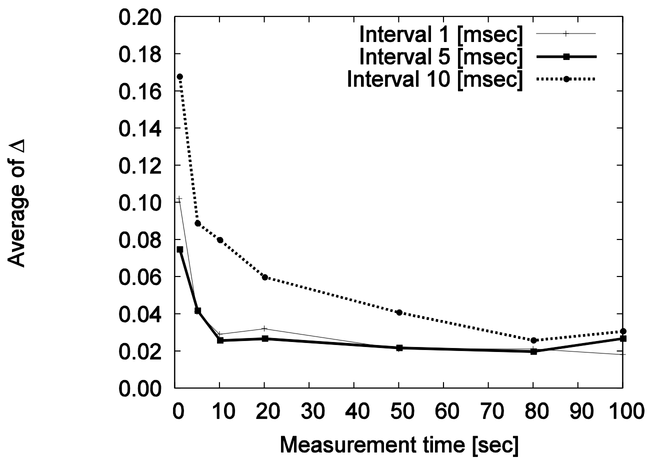

Fig. 9. Dependency of deviation on measurement time and sending interval of probe packets

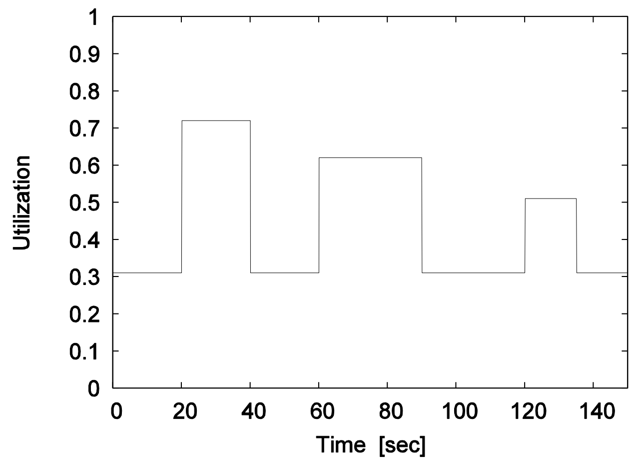

Fig. 10. Traffic pattern 1

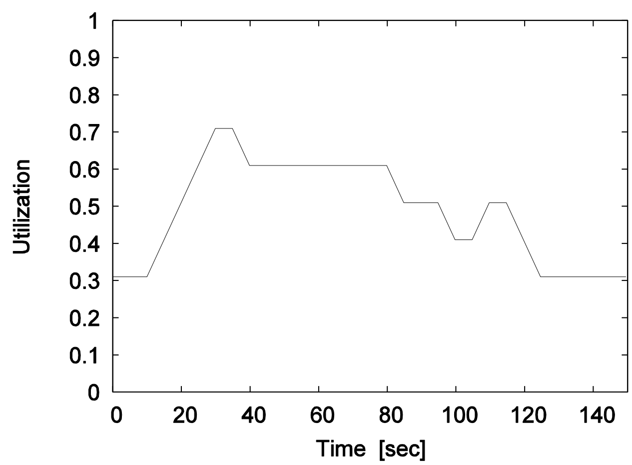

Fig. 11. Traffic pattern 2

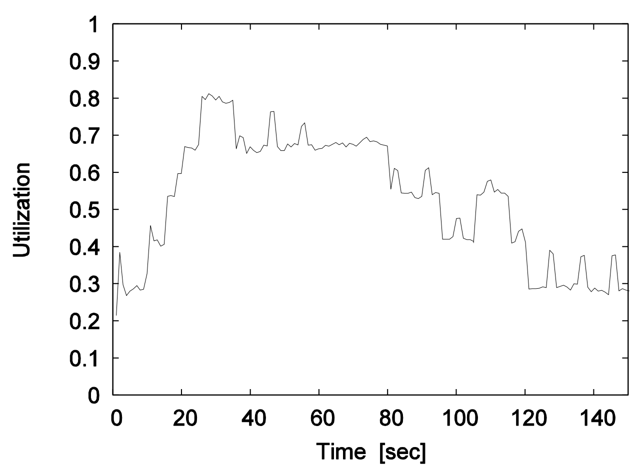

Fig. 12. Traffic pattern 3

C. Proposal follows change in link utilization

Link utilization changes from moment to moment, so we assessed the ability of the proposed scheme to follow these changes. In Figures 7 and 8, the load of link 2-3 is 0.3, while the load of link 3-4 varies.

Traffic Patterns

Figure 7 shows a network model that uses traffic patterns 1 and 2, which are presented in Figures 10 and 11, respectively. The size of request and reply packets is set to 32 [bytes]. Cross traffic has packet size of 1200 [bytes], 800 [bytes] and 500 [bytes]. The three cross-traffic flows, 1200 bytes, 800 bytes, and 500 bytes, have equal probability. Sending interval of request packets is set to 1 [ms] so the rate is 250 [Kbps].

In Figure 8 shows a network model that uses traffic pattern 3, which is presented in Figure 12. The size of request and reply packets is set to 32 [bytes]. The cross-traffic packet sizes are distributed as follows: 1200 [bytes] are 30%, 800 [bytes] are 10%, and 500 [bytes] are 60% [16]. Sending interval of request packets is set to 1 [ms] so the rate is 250 [Kbps].

Result of proposal follows change in link utilization

The jumping-window method is used to conduct the measurements [11]. During time interval (t, $t + T$), the observer estimates link utilization and $x(t)$ is denoted as link utilization at time t. Interval T, the size of window, is set at values of 5 [s] , 10 [s] and 15 [s]. Start time t is shifted by slide width, T. The value of estimated link utilization $U(t)$ is determined by applying a smoothing filter as defined in Eq. (10), α is the smoothing parameter and is set to 0.1.

$$U(t) = (1-\alpha)x(t) + \alpha\, x(t-T). \quad (10)$$

Estimated link utilization $U(t)$ is plotted in Figures 13, 14 and 15. Average of Δ and standard deviation on each window size is shown in Tables VII, VIII and IX.

In Tables VII and VIII, when window size T is 10 [s], $\Delta \leq 0.06$. This result shows that the proposed scheme estimates time-varying link utilization with an accuracy of 10% on the second time scale.

In addition, both tables show that Δ and standard deviation are smallest when window size T is 10 [s]. When T is small, Δ is large because of the small samples of RTT and when T is large, Δ is large because the plot point is delayed by large window size. This result shows that the appropriate window size, T, is 10 [s] for the configuration tested.

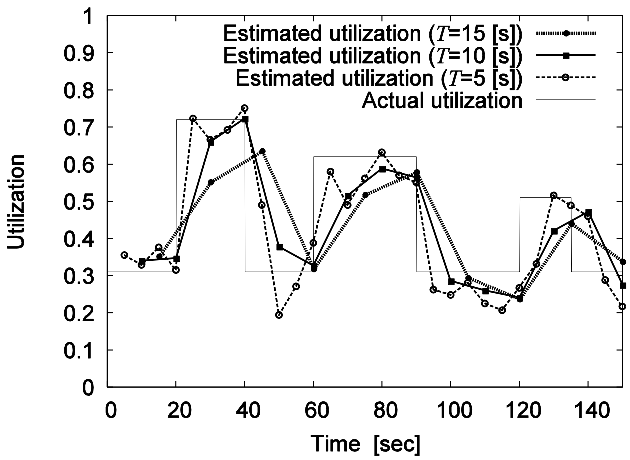

Fig.13. Proposal follows changes in link utilization in traffic pattern 1

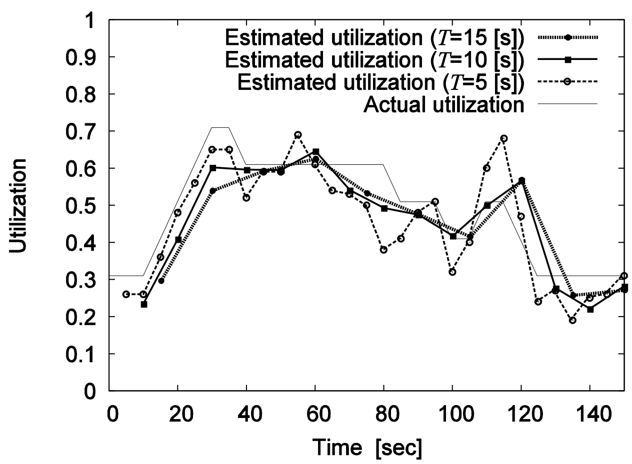

Fig.14. Proposal follows changes in link utilization in traffic pattern 2

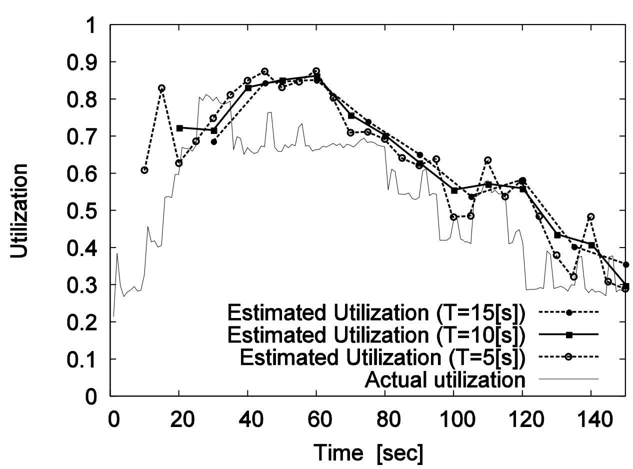

Fig.15. Proposal follows changes in link utilization in traffic pattern 3

In Table IX, the smallest Δ is 0.107 when window size T is 10 [s] or 5 [s]. In almost cases, Δs in Table VIII are worse than those of Tables VII and VIII when Δ is compared in the same window size, because of highly fluctuated traffic. In addition, The dependency of the window size is not clearly observed in terms of Δ and its standard deviation. This result shows that the proposed scheme estimates time-varying link utilization with bursty traffic with an accuracy of 13%

Table VII Proposal follows changes in link utilization in traffic pattern 1

Window size T [s]	Average of Δ	Standard deviation
5	0.062	0.048
6	0.084	0.089
7	0.107	0.108
8	0.075	0.057
9	0.100	0.088
10	0.056	0.039
11	0.116	0.111
12	0.102	0.072
13	0.122	0.075
14	0.133	0.108
15	0.087	0.091

Table VIII Proposal follows changes in link utilization in traffic pattern 2

Window size T [s]	Average of Δ	Standard deviation
5	0.065	0.049
6	0.080	0.068
7	0.075	0.061
8	0.087	0.081
9	0.095	0.072
10	0.059	0.045
11	0.065	0.047
12	0.089	0.063
13	0.063	0.062
14	0.079	0.090
15	0.164	0.113

Table IX Proposal follows changes in link utilization in traffic pattern 3

Window size T [s]	Average of Δ	Standard deviation
5	0.107	0.092
6	0.115	0.074
7	0.111	0.071
8	0.112	0.064
9	0.136	0.068
10	0.107	0.064
11	0.112	0.075
12	0.127	0.063
13	0.125	0.066
14	0.135	0.074
15	0.126	0.058

Comparison for conventional schemes

The proposed scheme impacts existing traffic only slightly, while SLoPS and TOPP creates strong impacts over short time periods. In the proposed scheme, the probing packet is just 32 [bytes]. The load of proposed scheme depends on sending interval of probe packets, however the maximum bandwidth occupied by probe packets in the scheme is only 250 [Kbps]. Table VIII compares the extra loads imposed by the proposed scheme to those of SLoPS and TOPP. The load of the proposed scheme is 2.5×10^{-4} , while SLoPS and TOPP scheme must exceed the residual bandwidth.

In addition the proposed scheme follows variation of link utilization on the second time scale. It is not feasible to follow variation of link utilization with the SLoPS and TOPP scheme, because SLoPS and TOPP scheme cause overload on the path. Impacting existing traffic only slightly, the proposed scheme can follows the variation without affecting existing traffic on the path.

Table X Comparison of extra loads imposed by SLoPS, TOPP, and proposed schemes (Ɛ > 0)

		Proposed scheme	
Utilization U	SLoPS/TOPP	Interval 10 [ms]	Interval 1 [ms]
0.5	0.5 + Ɛ	2.5×10^{-5}	2.5×10^{-4}
0.7	0.3 + Ɛ	2.5×10^{-5}	2.5×10^{-4}
0.9	0.1 + Ɛ	2.5×10^{-5}	2.5×10^{-4}

IV. CONCLUSION

This paper proposed a scheme based on RTT measurements to estimate upper bound of link utilization. In the proposed scheme, two RTTs are measured from a source host to both end nodes of the targeted link to obtain their probability distribution functions; the bandwidth used by the probe packets is much smaller than the available one. The upper bound of link utilization is estimated by deconvoluting the measured RTTs. The numerical results of the simulation showed that the proposed scheme estimates the upper bound of link utilization with an accuracy of 13%, while not degrading existing traffic and well follows the time-varying link utilization rate on the second time scale.

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