Measuring Available Bandwidth of Multiple Parts on End-to-end Network Path

Kazumasa Koitani*, Go Hasegawa†, Masayuki Murata*
*Graduate School of Information Science and Technology, Osaka University
1–5 Yamadaoka, Suita, Osaka, Japan
Email: {k-koitani, murata}@ist.osaka-u.ac.jp
†Cybermedia Center, Osaka University
1–32 Machikaneyamacho, Toyonaka, Osaka, Japan
Email: hasegawa@cmc.osaka-u.ac.jp

***Abstract*—The available bandwidth on an end-to-end network path is an important metric for detecting network congestion, adapting transmission rate, configuring paths and topologies on overlay networks, and so on. The existing available bandwidth measurement techniques aimed only at knowing available bandwidth of the bottleneck part on the path and most of them do not specify where is the bottleneck, and they do not measure available bandwidth of each part of the path separately. Also, they can not measure available bandwidth of multiple parts on the path. In this paper, we propose a simultaneous measurement method of available bandwidth of multiple parts on an end-to-end network path. The proposed method estimates the available bandwidth based on changes in packet sending and arrival intervals under the situation where intermediate routers on the path can record time on incoming packets as a timestamps. We present extensive simulation results of the proposed method and confirm that it can accurately measure available bandwidth of each part on the path even when the available bandwidth of the sender-side network is smaller than that of the receiver-side network.**

***Index Terms*—available bandwidth, network measurement, SLoPS, timestamp**

I. Introduction

The amount of the Internet traffic is rapidly increasing [1] due to recent wide spread of IP-reachable networked devices including smartphones, tablets, and laptop PCs. Also, various technologies for access and backbone networks are emerging, that makes the structure of the Internet more complex and heterogeneous. In such environment, bandwidth-related informations on an end-to-end network path is quite important for assuring the quality of network applications. Especially, the available bandwidth on an end-to-end network path is an important metric for detecting network congestion, adapting transmission rate, configuring paths [2] and topologies on overlay networks [3], and so on. On the other hand, the available bandwidth largely fluctuates [4] due to various network factors such as congestion. However, due to the current protocol structure of the Internet, applications on an endhost can not be explicitly notified of bandwidth-related information from the network. Therefore, it is important to obtain bandwidth-related information on end-to-end network paths [5] by conducting measurements at endhosts.

The available bandwidth on an end-to-end network path is determined by a bottleneck part, which has the smallest available bandwidth of the path. Existing tools for measuring available bandwidth of an end-to-end network path can obtain a value of available bandwidth at bottleneck part, but it can not determine where is the bottleneck part on the path except a tool *pathneck* [6], which specify the bottleneck part on the path. Also, they do not measure available bandwidth of each part of the path separately, while knowing the bottleneck location may enhance the quality of network applications. For example, assume that an end-to-end network path consists of a wireless network part and a wired network part and a sender-side endhost connects to the wireless network. Generally, wireless networks have higher bit error rate than wired networks. When we can obtain which part of the path is a bandwidth bottleneck and the bottleneck locates at the wired network, the sender-side endhost can configure the data rate of the wireless network to lower bit rate with smaller bit error rate, that enhances the quality of the network application. Such operations become available only when we obtain the available bandwidth information of both wireless network and wired network simultaneously. However, according to the authors' knowledge, there is no previous research on such end-to-end measurements of available bandwidth of multiple parts of the network path.

In this paper, we propose a simultaneous measurement method of available bandwidth of multiple parts on an end-to-end network path. The proposed method estimates available bandwidth based on the assumption that some of intermediate routers on the path can record time on packets as timestamps. We devide the end-to-end path into multiple parts by such intermediate routers and estimate the available bandwidth of each part of the path simultaneously, by observing intervals of incoming and outgoing packets on each network. For the estimation of available bandwidth we construct a simple but effective mathematical model of the relations between incoming and outgoing rates of packets.

To evaluate the performance of the proposed method, we conduct simulation experiments using ns-2 [7]. We evaluate the accuracy of the proposed method in various bandwidth settings including situations where the available bandwidth of the sender-side network is smaller than that of the receiver-side network.

The rest of this paper is organized as follows. Section II explains a principle of available bandwidth measurement based on the existing method. Section III proposes a simultaneous measurement method of the available bandwidth at multiple parts on an end-to-end network path. In Section IV we evaluate the measurement accuracy of the proposal method by simulation experiments. We conclude this paper and indicate future work in Section V.

II. Principle of End-to-End Measurement of Available Bandwidth

In this section, we explain a basic principle of measurement of the available bandwidth on an end-to-end network path. There are many existing tools for measuring end-to-end available bandwidth such as Cprobe [8], Pathload [9], pathChirp [10]. In these methods, a sender generates probe packets and sends them to a receiver at a certain rate. The receiver observes arrival intervals of probe packets, and determines whether or not sending rate of probe packets from the sender is larger than the available bandwidth of the path between the sender and receiver, by comparing sending and arrival intervals of the probe packets. Many of existing tools repeats this behavior with various sending rate to determine the available bandwidth accurately. In what follows in this section we briefly explain the mathematical background of the above method.

A. Network Model and Definitions

We assume that a path between a sender and a receiver is already determined and is not varied. Figure 1 depicts the network model in this section. The path consists of H links, and each of which is denoted as link i ($1 \leq i \leq H$). The physical bandwidth of the link i is denoted as C_i, and the available bandwidth of link i is A_i. The physical bandwidth C on an end-to-end network path is equal to that of the narrowest link, and it is represented as follows.

$$C \equiv \min_{i=1\ldots H} C_i \tag{1}$$

The average bandwidth untilization of link i at time t is denoted as $u_i(t)$. Then, the available bandwidth of link i at time t is represented as follows.

$$A_i(t) \equiv C_i(1 - u_i(t)) \tag{2}$$

The available bandwidth on an end-to-end network path is equal to that of the link which has smallest available bandwidth. Thus, the available bandwidth on an end-to-end network path at time t is represented as follows.

$$A(t) \equiv \min_{i=1\ldots H} C_i(1 - u_i(t)) \tag{3}$$

B. Available Bandwidth Measurement

We next explain a principle of available bandwidth on an end-to-end network path. It exploits the relationships between one-way delay from the sender to the receiver and sending arrival intervals of probe packets.

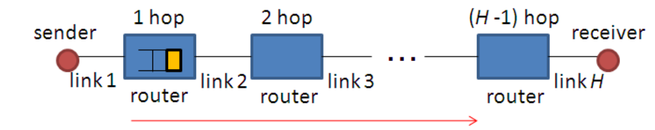


Fig. 1. Network model

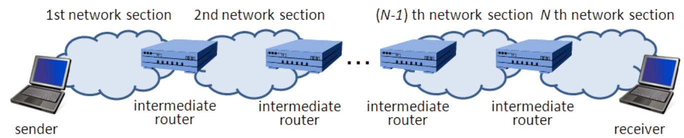


Fig. 2. Network model for measuring method of multiple parts on the path

The sender sends a sequence of K probe packets to the receiver. The sending time of k th ($1 \leq k \leq K$) probe packet from the sender is denoted as t_k, and the arrival time of the packet at the receiver is denoted as t'_k. The one-way delay of k th probe packet is represented as $D_k = t'_k - t_k$. We focus on the difference between k th and $(k+1)$ th one-way delays as follows.

$$\begin{aligned} \Delta D_k &= D_{k+1} - D_k \\ &= (t'_{k+1} - t_{k+1}) - (t'_k - t_k) \\ &= (t'_{k+1} - t'_k) - (t_{k+1} - t_k) \\ &= \Delta t'_k - \Delta t_k \end{aligned} \tag{4}$$

$\Delta t'_k$ in Equation (4) is an arrival interval of k th and $(k+1)$ th probe packets at the receiver, and Δt_k is a sending interval of the corresponding packets. When the sending rate of probe packets is larger than the available bandwidth, the value of Equation (4) becomes positive since arrival intervals becomes larger than the sending intervals. On the other hand, when the sending rate at the sender is equal to or smaller than the available bandwidth, the value of Equation (4) is roughly equal to 0 since we can expect the interval of packets remains unchanged when passing through the network. Note that we do not require the synchronization of clocks at senders and receivers to evaluate Equation (4), while the measurement of one-way delay requires it.

Therefore, by sending probe packets at a certain rate and observing their arrival at the receiver, we can determine whether the sending rate is larger than available bandwidth or not. Thus, repeating these operations enables the estimation of available bandwidth on an end-to-end network path.

III. Proposed Method

In this section, we propose a simultaneous measurement method of multiple parts on an end-to-end network path by extending the principle described in Section II.

We assume that a network path between a sender to a receiver is divided into multiple parts by intermediate routers, as depicted in Figure 2. Each part of the path is called as j th *network section*. The physical bandwidth of j th network section is denoted as $C(j)$, and the available bandwidth

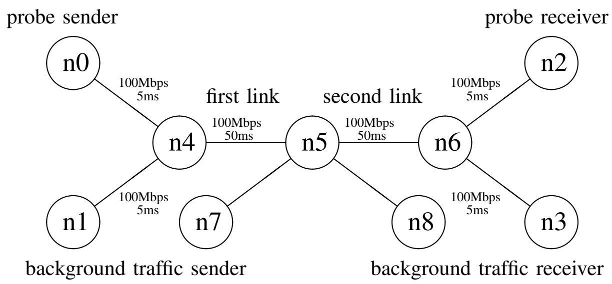


Fig. 3. Network model for simulation experiments

is denoted as $A(j)$. We focus on measuring the available bandwidth for all network sections by using probe packets sent from the sender to the receiver.

A. Possibility of Simultaneous Measurement

Measuring available bandwidth of a single network section can be conducted by injecting probe packets into the network section with various rates, that should be both larger and smaller than the actual available bandwidth of the network section. When all of the injecting rates of all probe packets is smaller than the actual available bandwidth, we can not measure the available bandwidth accurately. Therefore, to measure the avaialble bandwidth of all network sections on the path, one can consider the following condition needs to be satisfied.

$$\min_{1 \leq k < j} A(k) > A(j) \ (1 \leq j \leq N-1) \quad (5)$$

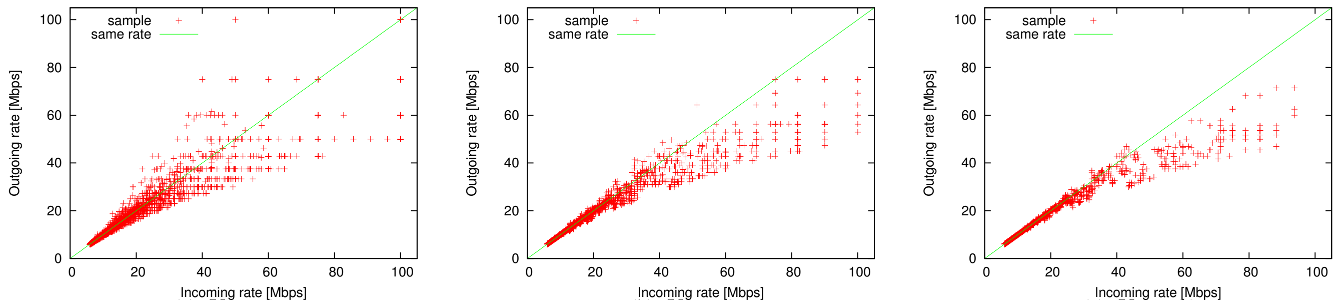
Equation (5) means that measuring available bandwidth is impossible when the available bandwidth of j th network section is smaller than that of $(j+1)$ th network section. This is inspired by the expectation that the rate at which probing packets going out of a certain network section would be equal to or smaller than the available bandwidth of the section. However, when the probing packets are injected at enough high rate, the outgoing rate would become larger than the actual available bandwidth of the network section [11]. This means that there is a possibility of measuring the available bandwidth of network sections even when Equation (5) is not satisfied. In what follows, we validate the possibility by simulation experiments using ns-2.

Figure 3 shows the network model used in the simulation experiments. The propagation delay of the link between n4 and n5 (we call it the *first link*) and that between n5 and n6 (the *second link*) is 50 [ms]. Other links have 5 [ms] delay. The physical bandwidth of all links in the network is 100 [Mbps]. Background traffic is sent from node n1 to node n8 via nodes n4 and n5 at X_1 [Mbps]. Another background traffic is sent from node n7 to node n3 via node n5 and n6 at X_2 [Mbps]. Therefore, the available bandwidth of the first link is $(100 - X_1)$ [Mbps], and that between n5 and n6 is $(100-X_2)$ [Mbps]. The background traffic is constructed from UDP packets whose sending intervals follows the exponential distribution with designated mean value. Probe packets are sent form node n0 to node n7 via nodes n4, n5, and n6, traversing the first and second links. The intervals of probe packets sent from node n0 is varied from 0.0001 [s] to 0.002 [s] in units of 0.00001 [s], which corresponds to the rate from 6 [Mbps] to 120 [Mbps]. The number of probe packets send at a time is K_0. The probe packet size is set to 1000 [Bytes] and the packet size of background traffic is set to 1500 [Bytes]. Under this settings, we observe incoming and outgoing rates of probe packets at the second link. We utilize the average rate of K_0 probe packets as the incoming and outgoing rates.

Figures 4, 5, and 6 show the simulation results, where we plot the relationship between incoming and outgoing rates of probe packets at the second link when $K_0 = 2$, 6, and 10. Figure 4 plots the results when $X_1 = 30$ and $X_2 = 70$. In the case, the actual value of the available bandwidth at the second link is 70 [Mbps], which is larger than that of the first link (30 [Mbps]) and Equation (5) is satisfied. Therefore, we expect the available bandwidth measurement of second link can be done easily. This can be confirmed by Figure 4 where the incoming rate varies from small values to large values close to 100 [Mbps], and that when the incoming rate is large, the outgoing rate becomes smaller than the incoming rate.

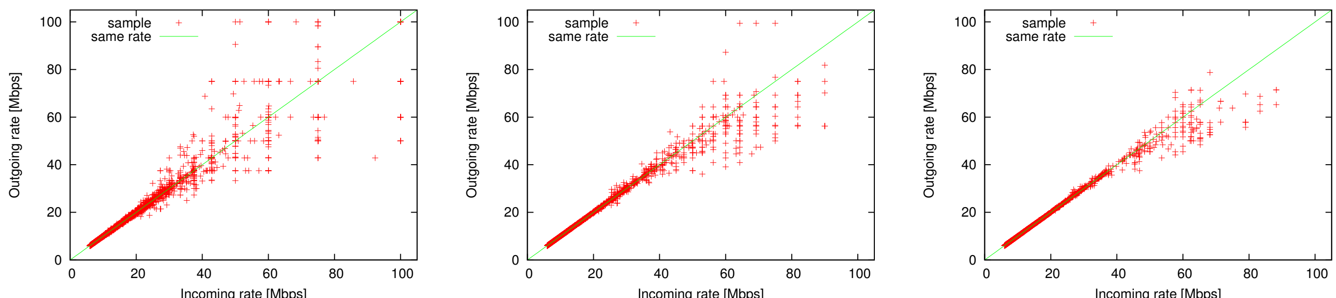
Figure 5 show the case where $X_1 = 50$ and $X_2 = 40$. Since the actual available bandwidth of the first and second links are $X_1 = 50$ and $X_2 = 60$, respectively, Equation (5) is not satified. However, we can observe from Figure 5 that a significant portion of probe packets are injected into the second link at rate higher than 50 [Mbps], regardless of the value of K_0. Also, when the incoming rate is high, the outgoing rate of probe packets tends to become smaller than the incoming rate, especially with larger K_0. These results means that we can utilize the principle described in Subsection II-B to measure the available bandwidth of the second link, whereas Equation (5) is not satisfied. In Figure 6, we plot the results when $X_1 = 50$ and $X_2 = 30$, where the actual available bandwidths of the first and second links are 50 [Mbps] and 70 [Mbps], respectively. We can observe the similar tendency to Figure 5 and we can expect that the measurement of the second link is possible. However, the upper limit of incoming rate is a little smaller than that in Figure 5 especially with large value of K_0, that may degrade the measurement accuracy of the second link. This is because the actual available bandwidth of the first link is 50 [Mbps], which is quite small compared with physical bandwidth (100 [Mbps]).

We next focus on the effect of K_0. In the case of small K_0 (Figures 4(a), 5(a), and 6(a)), we can not observe the stable relationship between incoming and outgoing rates of probe packets. On the other hand, too large value of K_0 would results in that incoming and outgoing rates are smoothed and their difference becomes invisible, as partly observed by comparing Figures 4(b) and 4(c), Figures 5(b) and 5(c), and Figures 6(b) and 6(c). These effect may affect the measurement accuracy, which is confirmed in Section IV. Futhermore, larger K_0 requires the larger number of probe packets to obtain enough probing samples. Thus, when we set the parameter K_0, we



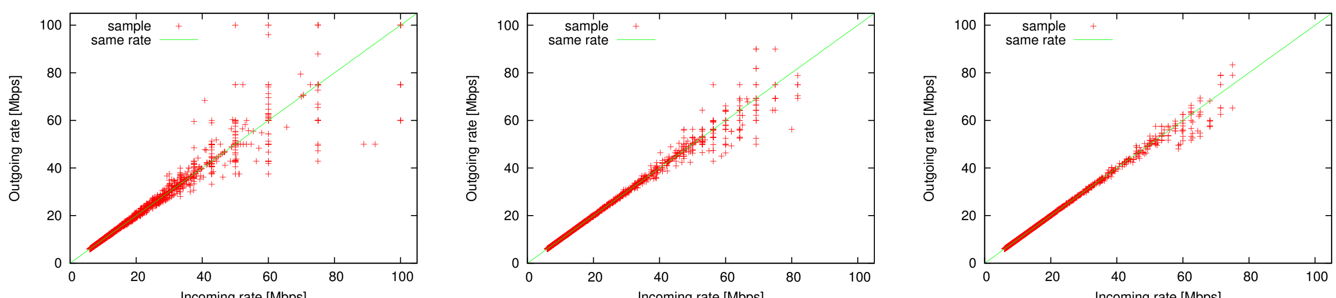
(a) $K_0 = 2$ (b) $K_0 = 6$ (c) $K_0 = 10$

Fig. 4. Relationship between incoming and outgoing rates with $X_1 = 30$ and $X_2 = 70$



(a) $K_0 = 2$ (b) $K_0 = 6$ (c) $K_0 = 10$

Fig. 5. Relationship between incoming and outgoing rates with $X_1 = 50$ and $X_2 = 40$



(a) $K_0 = 2$ (b) $K_0 = 6$ (c) $K_0 = 10$

Fig. 6. Relationship between incoming and outgoing rates with $X_1 = 50$ and $X_2 = 30$

must consider the measurement accuracy and the amount of probe packets to obtain the measurement results.

B. Proposal Method

The measurement principle explained in Subsection II-B based on the observation of a single pair of incoming and outgoing rates of probe packets on the network. Therefore, the existing measurement methods can obtain only the available bandwidth of the bottleneck part of the network. To measure the available bandwidths of multiple network sections, we assume that the intermediate routers in Figure 2 can record the times at which probe packets passing through the router. The proposed method utilize those timestamps to estimate the available bandwidth of each network section.

We propose a method to give the estimation result of the

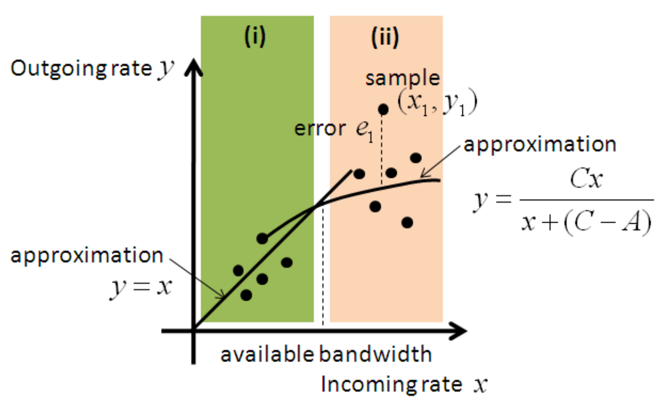


Fig. 7. Computation of available bandwidth in proposed method

available bandwidth based on probing results as shown in Figure 5. The simulation results in Figure 5 can be abstracted into a simple mathematical model depicted in Figure 7. The probing results can be divided into two regions (i) and (ii). In region (i), the sending rate of probe packets is less than the actual value of the available bandwidth. Therefore, the incoming and outgoing rates becomes almost equal in the region. In region (ii), on the other hand, the probing packets are injected at higher rate than the actual available bandwidth. In this case the outgoing rate would be smaller than the incoming rate. We utilize a fluid model to determine the outgoing rate of probe packets from incoming rates and the actual available bandwidth. We denote the incoming rate of probe packets as x [Mbps] and the outgoing rate of probe packets when incoming rate is x is denoted as $y(x)$ [Mbps]. The physical bandwidth and the available bandwidth is denoted as C [Mbps] and A [Mbps]. Then, the model in Figure 7 can be represented as follows.

$$y(x) = \begin{cases} x & x \leq A \\ \frac{Cx}{x+(C-A)} & x > A \end{cases} \tag{6}$$

The proposed method first gathers probing samples as in Figure 5, and determines the available bandwidth, which corresponds to A in Equation (6), by a simple regression of the equation to fit to the probing samples. This regression in the proposed method is the modified point from TOPP [12]. We explain the proposed method in detail.

The sender sends K probe packets, which is denoted as P_i ($1 \leq i \leq K$), at a certain rate. We focus on successive K_0 probe packets from K packets, which consists of P_i, P_{i+1}, ..., and P_{i+K_0-1} ($1 \leq i \leq K - K_0 + 1$), and calculate the incoming and outgoing rates from timestamps at intermediate routers, that are denoted as x_i [Mbps] and y_i [Mbps], respectively. That is, (x_i, y_i) is i th probing sample. Note that we can obtain $(K - K_0 + 1)$ samples from K packets. The sender sends many probing packets at various rates, and obtains N_{all} samples. We next divide these samples based on their incoming rates to obtain average values. We set the resolution of rate to R_0 [Mbps]. We then calculate the average value of incoming and outgoing rates of samples for each rate. We denote the averaged samples as $(\hat{x_k}, \hat{y_k})$ $(1 \leq k \leq \lceil C(j)/R_0 \rceil)$. We assume that the physical bandwidth of j th network section is already known as $C(j)$. We obtain the estimation results of the available bandwidth of j th network section by the below equation,

$$\bar{A}(j) = \underset{A(j)}{\operatorname{argmin}}\ e(A(j)) \tag{7}$$

where $e(A(j))$ is calculated as follows.

$$e(A(j)) = \sum_{\hat{x}_i \leq A(j)} (\hat{y}_i - \hat{x}_i)^2 + \sum_{\hat{x}_i > A(j)} \left(\hat{y}_i - \frac{C(j) \cdot \hat{x}_i}{\hat{x}_i + (C(j) - A(j))} \right)^2 \tag{8}$$

IV. Performance Evaluation

We evaluate the performance of the proposed method by conducting simulation experiments using ns-2.

A. Experimental Environment

We utilize the same network model as in Subsection III-A, depicted in Figure 3. The available bandwidth of the first link, which locates between nodes n4 and n5, is denoted as $A(1)$ [Mbps], the available bandwidth of the second link, which locates between nodes n5 and n6, is denoted as $A(2)$ [Mbps]. We vary $A(1)$ and $A(2)$ from 10 [Mbps] to 90 [Mbps] with 10 [Mbps] step by changing background traffic rates. In this environment, we measure the available bandwidth of the second link by the proposed method. The parameters K and R_0 of the proposed method is set to 20 and 1 [Mbps].

B. Results

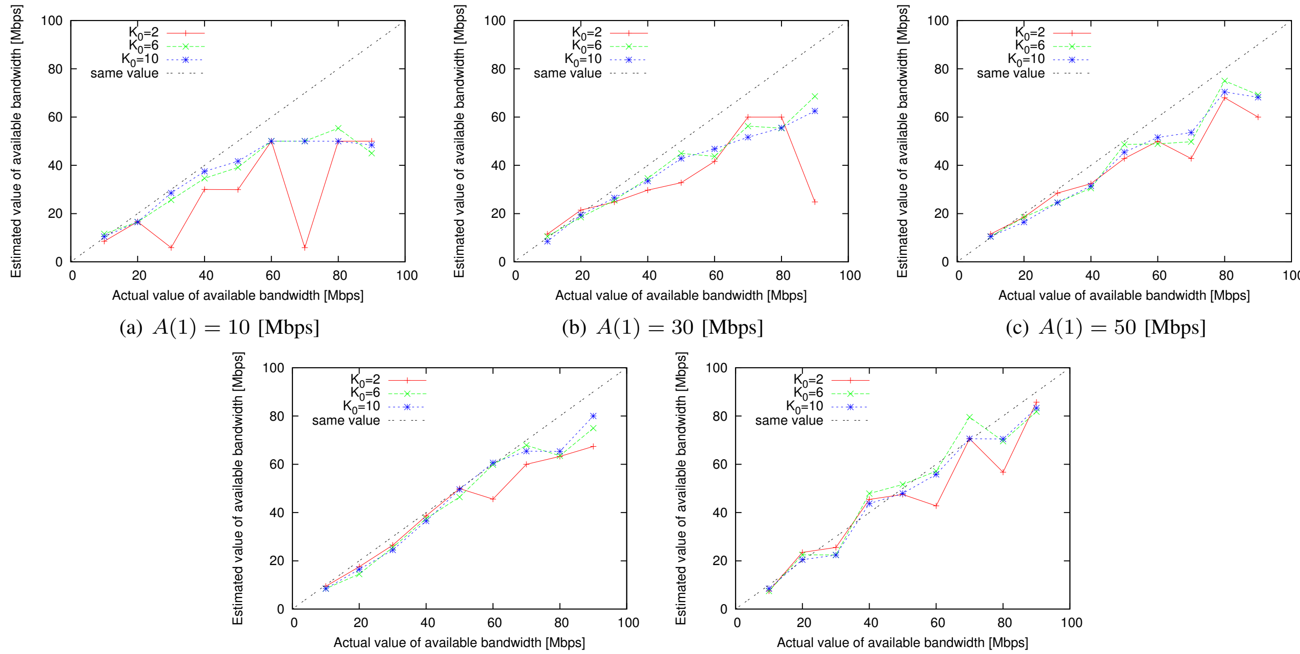
Figure 8 exhibits the simulation results on the measurement accuracy of the available bandwidth of the second link. Each graph in Figure 8 has the different values of the actual available bandwidth of the first link ($A(1)$). In each graph we plot the relationship between actual and estimated values of the available bandwidth of the second link in cases of $K_0 = 2$, 6, and 10.

These figures indicate that the available bandwidth at second link is measured accurately regardless of actual values of available bandwidths of two links ($A(1)$ and $A(2)$). Especially when $A(2) < A(1)$, which satisfies Equation (5), the available bandwidth is measured with high accuracy. On the other hand, when $A(2) > A(1)$, which does not satisfy Equation (5), the measurement accuracy remains reasonable. However, especially when $A(2)$ becomes close to 100 [Mbps], the measurement accuracy degrades especially $A(1)$ is small. This is because of the decrease in probing results whose incoming rate is larger than $A(2)$. We can also observe from Figure 8 that to obtain accurate measurement results we should avoid from setting $K_0 = 2$ since the measurement results have significant fluctuations. This is because the relationships between incoming and outgoing rates becomes unstable, as shown in Figures 4(a), 5(a), and 6(a).

Figure 9 depicts the average measurement errors as a function of K_0. Here, the measurement error is defined as follows by using actual and estimated values of available bandwidth, which are denoted as A and $\bar{A}$, respectively.

$$e = \frac{|A - \bar{A}|}{A} \tag{9}$$

The length of the error bar in Figure 9 represents the standard deviation. The figure indicates that when $K_0 \leq 3$, the measurement accuracy is low as compared to the case of $K_0 \geq 4$. This is because in cases of small K_0, the intervals of probe packets is largely affected by changes of background traffic. On the other hand, when $K_0 \geq 4$, the measurement error remains almost unchanged. From these results, considering the network load by probe packets and the measurement accuracy, we should choose $K_0 = 4$ for the



(a) $A(1) = 10$ [Mbps]
(b) $A(1) = 30$ [Mbps]
(c) $A(1) = 50$ [Mbps]
(d) $A(1) = 70$ [Mbps]
(e) $A(1) = 90$ [Mbps]

Fig. 8. Measurement results of available bandwidth in simulation experiments

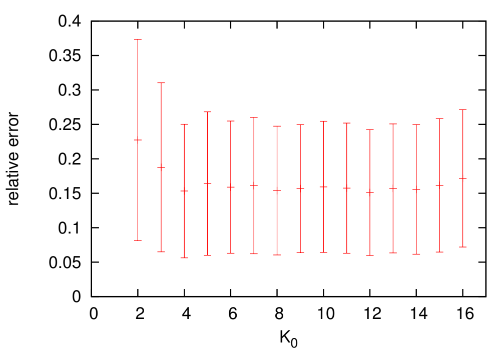


Fig. 9. Effect of K_0

simulation environments in this paper. The parameter tuning issues for various network situations is one important topics of the future research.

V. Conclusion

In the paper, we proposed the simultaneous measurement method of multiple parts on an end-to-end network path. The proposed method simply extends the measurement principle utilized in existing measurement tools by adding a small function to intermediate routers. We validated the performance of the proposed method by simulation experiments and obtained the results that the available bandwidth of multiple parts of the path can be measured with reasonable accuracy even when the available bandwidth of the receiver-side network is larger than that of the sender-side network.

In future work, we plan to propose to determine the number of probe packets to decrease the measurement overhead while keeping the measurement accuracy.

References

[1] "Hobbes' Internet Timeline." available at http://www.zakon.org/robert/internet/timeline/.
[2] J. Kim, J. Yun, M. Yoon, K. Cho, H. Lee, and K. Han, "A Routing Metric Based on Available Bandwidth in Wireless Mesh Networks," in *Proceedings of ICACT 2010*, February 2010.
[3] L. T. M. Cao, G. Hasagawa, and M. Murata, "ImTCP: TCP with an Inline Measurement Mechanism for Available Bandwidth," *Computer Communications Journal special issue of Monitoring and Measurements of IP Networks*, vol. 29, pp. 1614–1626, June 2006.
[4] E. Ko, D. An, and I. Yeom, "Dealing with Sudden Bandwidth Changes in TCP," in *Proceedings of IEEE ICC 2008*, pp. 3007–3011, May 2008.
[5] J. Strauss, D. Katabi, and F. Kaashoek, "A Measurement Study of Available Bandwidth Estimation Tools," in *Proceedings of IMC 2003*, pp. 39–44, October 2003.
[6] N. Hu, L. E. Li, Z. M. Mao, P. Steenkiste, and J. Wang, "Locating Internet Bottlenecks: Algorithms, Measurements, and Implications," in *Proceedings of ACM SIGCOMM 2004*, pp. 41–54, September 2004.
[7] "ns-2 web page." available at http://isi.edu/nsnam/ns/.
[8] C. Robert L and M. E. Crovella, "Dynamic Server Selection using Bandwidth Probing in Wide-Area Networks," tech. rep., Boston University, 1996.
[9] M. Jain and C. Dovrolis, "End-to-End Available Bandwidth: Measurement Methodology, Dynamics, and Relation with TCP Throughput," in *Proceedings of ACM SIGCOMM 2002*, pp. 295–308, August 2002.
[10] V. J. Ribeiro, R. H. Riedi, R. G. Baraniuk, J. Navratil, and L. Cottrell, "pathChirp: Efficient Available Bandwidth Estimation for Network Paths," in *Proceedings of PAM 2003*, pp. 1–11, April 2003.
[11] C. Dovrolis, P. Ramanathan, and D. Moore, "What do packet dispersion techniques measure?," in *Proceedings of INFOCOM 2001*, vol. 2, pp. 905–914, April 2001.
[12] B. Melander, M. Bjorkman, and P. Gunningberg, "A New End-to-End Probing and Analysis Method for Estimating Bandwidth Bottlenecks," in *Proceedings of GLOBECOM 2000*, vol. 1, pp. 415–421, November 2000.