Accurate Loss Estimation Technique Utilizing Parallel Flow Monitoring

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***Abstract*—For the design of delay/loss sensitive applications (e.g., audio/video conferencing, IP telephony, or telesurgery), it is important to accurately measure metrics along an end-to-end path. To improve the accuracy of end-to-end delay measurements, in our previous work, we have proposed a parallel flow monitoring technique. In this technique, delay samples of a target flow increase by utilizing the observation results of other flows sharing the source/destination with the target flow. In this paper, we extend this delay measurement technique to loss measurements and enable it to fully utilize information of all flows including flows with different source and destination. We confirmed that the proposed method reduces the error of loss rate estimations by 57.5% on average in ns-3 simulations.**

***Index Terms*—Active Measurement, Packet Loss Rate, Parallel Measurement, Probe Packet, QoS Monitoring**

I. INTRODUCTION

In network performance evaluation, end-to-end loss and delay are both fundamental metrics, and accurate measurements for these end-to-end metrics are key techniques. Internet Service Providers (ISPs) concludes Service Level Agreements (SLAs) with users. ISPs are under an obligation to keep their service levels in the agreements, and therefore monitor the metrics as an SLA monitoring. Additionally, it is well known that real-time applications are sensitive to end-to-end packet loss or delay. Advanced SLAs which stipulate about metrics along an end-to-end path are needed for delay/loss sensitive applications. Hence, the accurate measurement of end-to-end metrics is important for SLA monitoring, in order to provide advanced SLAs for delay/loss sensitive applications.

As a measurement technique of end-to-end metrics for networks, an active measurement in which probe packets are injected into a network is commonly used, and various measurement tools for active measurements have been proposed in prior works [1]–[6]. It is tried to improve accurate measurement without increasing the number of probe packets in the literature [7]–[9] since an increase of the number of probe packets leads to communication overheads and the intrusiveness problem [6], [10]. In the modern Internet, a large delay (that exceeds 150 [ms] as mentioned in ITU-T Recommendation G.114 [11]) rarely occur. Packet losses are also rare events as ITU-T Recommendation Y.1541 defines QoS class with upper bounds 1.0×10^{-5} of end-to-end loss rate for emerging applications. It is difficult to capture such rare events using a limited number of the probe packets.

While most of the prior works utilize only one probe flow to measure the end-to-end metric regarding one path, we have proposed a parallel flow monitoring method in which delay on a flow is accurately measured by utilizing the observation results of flows sharing the source/destination [12], [13]. In daily operations, ISPs are monitoring end-to-end metrics of the multiple paths on their network in parallel. The method in reference [12] utilizes this parallel monitoring.

In this paper, based on the delay measurement method in reference [12], we propose a loss measurement method that fully utilizes flows, including flows with different source and destination. We extend the delay measurement method to a loss measurement with a weighted loss estimator. In the proposed method, when a loss rate on a path of a target probe flow is estimated, information regarding lost probe packets of the other probe flows is utilized. As we mentioned above, it is difficult to capture packet loss events by the limited number of probe packets in a target probe flow since the packet losses are rare events. Even if a target probe flow fails to capture loss events, the proposed method can estimate the loss rate on the path of the target probe flow since another probe flow may capture loss events. Therefore, the proposed method transcends a fundamental accuracy bound of conventional active measurements of the loss rate. The method and network tomography are totally difference because our method estimate loss rate along a path. Additionally, we improve the accuracy of the extended method by fully utilizing information regarding all

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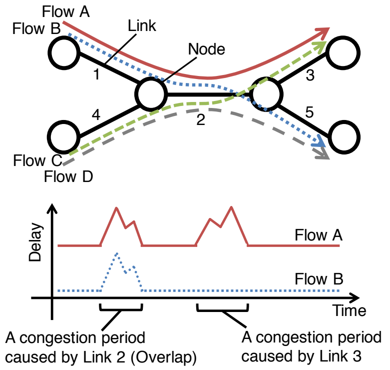

Fig. 1. Overlap of queueing delay processes in a congestion period.

flows with recursive conversion of the information regarding the other flows. The proposed method utilizes the information of all probe flows that share a part of the path with a target probe flow though the method in reference [12] only utilize information of flows that has the same source/destination with a target probe flows.

The proposed method is extremely versatile under mild assumptions. The method does not require any internal information of a measured network, including a topology, and it only uses delay and loss of each flow. Note that the method does not assume that all possible paths in a network are simultaneously monitored. It can appropriately perform when only a part of paths in a network are monitored.

The rest of the paper is organized as follows. First, we mention a network model and assumptions in Section II. Next, Section III summarizes the parallel flow monitoring technique for a delay measurement in our previous study [12]. In Section IV, we explain a proposed loss measurement technique that fully utilizes information regarding all flows in a network. In Section V, we evaluate the proposed method through simulations. Finally, we conclude the paper and mention future works in Section VI.

II. A Network Model and Assumptions

Since the method we propose in this paper is based on the method [12], most of the assumptions in reference [12] are inherited to this paper. A wired network considered within the scope of this work is represented by a directed graph. A packet is delivered from a source to a destination along a path. Paths are stable in a measurement period (generally within several minutes) since paths are not changed frequently. Packets are delayed and may be lost at vertices or links on a path. We assume that an end-to-end delay consists of propagation delay and queueing delay since both delays are dominant in the modern Internet [14]. Propagation delay can be regarded to be a constant for a path while queueing delay dynamically changes reflecting traffic status.

In this paper, we assume that most of loss events are caused by buffer overflows in interfaces placed on links with congestions. Inevitably, packet loss events highly depend on queueing delay. We assume that links with large queueing delay, i.e. links with many packet loss events, are sparse among all links in a network, and the ratio of periods with large queueing delay on a link to other periods is small. The validity of the assumption can be confirmed since the average link utilization of the modern Internet is maintained low [15].

Though the metric we want to measure is loss rate along a path in wired packet networks, we utilize delay information to improve an accuracy of loss rate measurement. To measure packet loss rate and packet delay on paths, probe packets are periodically injected for all or a part of paths on a network. A delay or loss experienced by a probe packet can be obtained by matching the packets at the source and the destination.

III. Parallel Flow Monitoring for Delay

Since we assume sparsity of congested links, queueing delay processes within a congestion period on multiple paths that have common links frequently overlap (see Fig. 1), and the samples within the congestion periods can be converted. In the method in reference [12], the ith sample for Flow A is expressed by $(t^i_{\mathrm{A}}, x^i_{\mathrm{A}})$ where t^i_{A} and x^i_{A} denote injection time and experienced delay of the ith probe packet, respectively. A congestion period is observed as consecutive samples that are larger than a threshold x_{th}. The jth congestion periods on the path of Flow A is denoted as $X_{\mathrm{A},j}$. If there are congestion periods of multiple flows whose start and end times are respectively almost the same (i.e., they are closer than a constant probe interval δ), the congestion periods are passed to a clustering process. Delay samples in the congestion periods are formatted to n-dimensional vectors, and the vectors are divided into clusters for each common link that causes a large delay. A clustering technique in machine learning is utilized to divide them into clusters. A queueing delay process captured by probe flows in the same cluster are determined to be overlapped, and the delay samples are converted between each other, by modifying the injection time and delay to that of the target flow. By the conversions, the number of delay samples of each flow is increased, thereby improving the accuracy of the delay measurement.

IV. Parallel Flow Monitoring for Loss Rate

In this paper, we extend the method [12] introduced in Section III to a loss measurement and improve its accuracy by utilizing information of all flows including flows with different source and destination. By utilizing all flows, the proposed method makes it possible to capture loss events that occur with extremely low probability.

A. *Extension for Loss Rate Measurements*

The proposed method achieves accurate loss rate measurements by uniting samples of loss events. As with the method in reference [12], the uniting in the proposed method is based on delay information, though the metric we want to measure is loss rate in the proposed method. In the proposed method, samples that capture loss events are recorded for each congestion periods, and samples are united each other at the

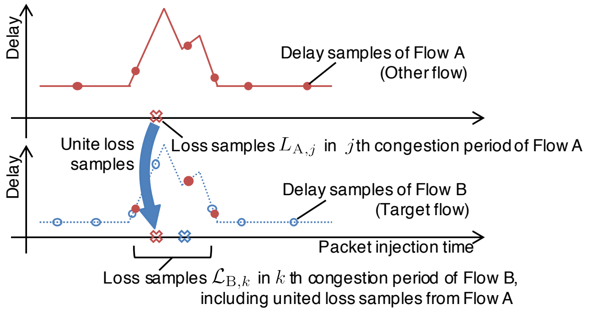

Fig. 2. United samples of loss events.

time of conversion of delay samples. Since we assumed that the main cause of packet loss is buffer overflows, most of packet loss events occur within congestion periods. Therefore, we can consider that loss events within a congestion periods occur at the link which causes the congestion. First of all, samples $L_{\mathrm{A},j}$ of loss events between the first and last samples in delay samples $X_{\mathrm{A},j}$ are recorded. A loss sample in $L_{\mathrm{A},j}$ is defined as $(t^i_{\mathrm{A}}, \infty)$ that corresponds to a lost probe packet. Based on the method in reference [12], samples $X_{\mathrm{A},j}$ for delay are converted each other, thereby obtaining samples $\mathcal{X}_{\mathrm{A},j}$ which includes converted samples. When the samples $X_{\mathrm{A},j}$ are converted to the kth congestion period on the path of Flow B, samples $L_{\mathrm{A},j}$ of loss events are united to samples $L_{\mathrm{B},k}$ of loss events within the kth congestion period on the path of Flow B. As a result, the samples $\mathcal{L}_{\mathrm{B},k}$ which includes united samples within the kth congestion period on the path of Flow B are updated to $\mathcal{L}_{\mathrm{B},k} \cup L_{\mathrm{A},j}$. Note that $\mathcal{X}_{\mathrm{A},j}$ and $\mathcal{L}_{\mathrm{A},j}$ respectively include converted and united samples from other flows while $X_{\mathrm{A},j}$ and $L_{\mathrm{A},j}$ represent original samples of Flow A.

To provide an unbiased estimator of loss rate on each path, samples should be weighted since the samples of loss events in the proposed method are biased on a time-space, while most of conventional loss measurements using active probes assume that probe packets are uniformly distributed. The weight w_s of a sample s is given as $|X_{\mathrm{A},j} \cup L_{\mathrm{A},j}| / |\mathcal{X}_{\mathrm{A},j} \cup \mathcal{L}_{\mathrm{A},j}|$ for $s \in \mathcal{L}_{\mathrm{A},j}$. $\sum_j \sum_{s \in \mathcal{L}_{\mathrm{A},j}} w_s / (|X_{\mathrm{A}}| + |L_{\mathrm{A}}|)$ provides an estimator of loss rate on the path of Flow A, where $|X_{\mathrm{A}}|$ and $|L_{\mathrm{A}}|$ denote the number of all delay samples and loss samples of flow A, respectively.

B. Recursive Conversion Technique to Utilize All Probe Flows

By repeatedly converting samples obtained from each probe flow, the proposed method utilizes information of all probe flows that include flows with different source and destination. Even if both source and destination are different, flows that share a part of paths includes information of the target flow.

By checking whether conversion of samples is possible for all pairs of congestion periods of all probe flows, trees that represent dependency of conversions are generated for each congestion period (see Fig. 3). The proposed method recursively converts/unites samples from the leaves to the root of the tree. The computational complexity of the conversion process of the proposed method is $O(NM)$ for each congestion, where N and M denote the number of flows and the maximum number of samples in a congestion, respectively.

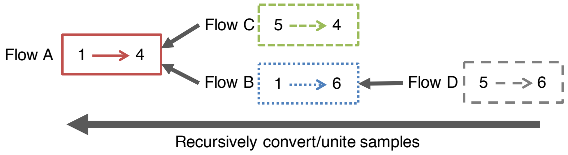

Fig. 3. An example of a dependency tree for a recursive conversion.

TABLE I
TYPES OF TRAFFIC IN OUR SIMULATIONS.

Stationary	Packet size	600 [Byte]
	Traffic pattern	Poisson arrivals
	Traffic intensity	388.8 [Kbps] (4% of a link capacity)
Bursty	Packet size	500 [Byte]
	Traffic pattern	On/off process with periodic arrivals in bursty periods
	Traffic intensity	10,000 [Kbps] in bursty periods
		0 [bps] in idle periods
	Bursty period	Exponential distribution with mean 1.0 [s]
	Idle period	Exponential distribution with mean 100.0 [s]
Probe	Packet size	74 [Byte]
	Traffic pattern	Periodic arrivals
	Packet intervals δ	200 [ms]

V. EVALUATIONS

We perform ns-3 [16] simulations to confirm that the number of captured loss events increases and accuracy of a loss rate estimation is improved.

A. Simulation Settings

The network we simulated resembles Internet2 topology [17] with 9 nodes and 13 links whose capacities are 15.552 [Mbps] (see Fig. 6). The numerical values written beside the links in Fig. 6 indicate propagation delay, and we set them proportional to the distance between the nodes in Internet2.

1 probe flow and 2 user flows listed in Table I stream between all pairs of 9 nodes (i.e. $9 \times 8 = 72$ flows for each type in the entire network). Phases of packet injection are randomized while probe packets are injected periodically. The probe packets are commonly used for the proposed method and the conventional method. Since the link capacity is uniformly 15.552 [Mbps], if two or more flows of bursty traffic are joined at the link, traffic intensity on a link temporally exceeds the link capacity, thereby occurring a buffer overflow due to temporal capacity shortage. Though the congested links are sparse, congestions on multiple links can occur at the same time. Each node is configured with a drop-tail queue whose maximum size is 1024 for all interfaces. The simulation time is 1005.0 [s] and we only use the data from 5.0 [s] to 1005.0 [s].

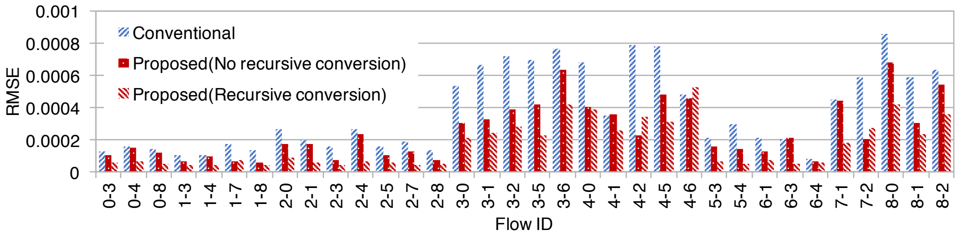

Fig. 4. RMSE of loss rate estimations.

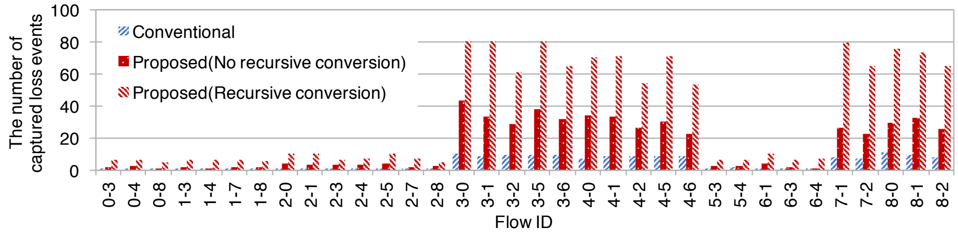

Fig. 5. The number of loss events that is captured by probe flows for each path.

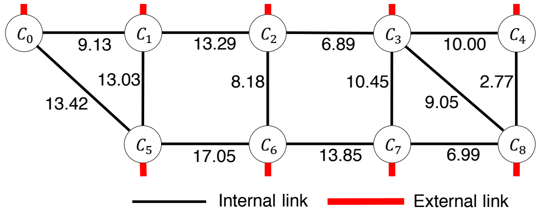

Fig. 6. Network topology on evaluations.

The parameters of the proposed method are set as follows. The threshold x_{th} is set to 0.01 [s]. We use Minimum Entropy Clustering (MEC) [18] for clustering, and its radius parameter r is set to 0.1.

B. Simulation Results

We evaluate the accuracy of the loss rate estimation of the proposed method. The simulation was repeated 10 times by changing the phase of the probe packet injection time. Root Mean Squared Errors (RMSE) of loss rate measurements are calculated, and the result is shown in Fig. 4. To calculate RMSE, we refer loss rate experienced by packets of the stationary user flows as true values of loss rate estimations since the rate of the stationary user flows is extremely high than that of probe flows. The maximum loss rate experienced by stationary user flows was about 1.7×10^{-3}. The conventional estimator in this section is simply calculated as the ratio of the number of loss samples to the total number of samples. Note that it is not the method in reference [12]. The simple estimator is adapted by many prior works [8], [9], [19]. The results on paths in which any loss event is not captured by the stationary user flow are omitted in Fig. 4. In the results of no recursive conversion in Fig. 4, only samples of flows that have the same source/destination with a target probe flow are converted.

We can confirm that RMSE of each probe flow is reduced by the proposed method. Compared to the conventional method, the proposed method without recursive conversion provides 31.3% reduction of RMSE on average. Since the proposed method with recursive conversion achieves 57.5% reduction of RMSE on average, it can be confirmed that recursive conversion achieves further improvement in accuracy. Therefore, the proposed method can improve the accuracy of the loss rate measurement, though the number of probe packets in the entire network does not increase compared to that of the conventional method. The accuracy improvement is caused by the increase of samples that capture loss events. The increase of the samples is shown in Fig. 5. The recursive conversion unites samples form more flows than the no recursive conversion, thereby increasing the number of captured loss events. In principle, it is impossible for the conventional method to estimate the loss rate less than 2.0×10^{-4} since the number of the probe packets par flow is 5000 in the simulation. However, the proposed method overcomes this fundamental limitation in accuracy.

VI. CONCLUSIONS AND FUTURE WORKS

We proposed a loss measurement method that fully utilizes flows, including flows with different source and destination in this paper. The proposed method is based on the delay measurement method in reference [12]. Through simulations on ns-3 simulator, we confirmed that the proposed method can reduce estimation errors by 57.5% on average.

As future research, we plan to develop highly accurate delay/loss tomography using the parallel monitoring technique. Additionally, we also have a plan to implement the proposed method for a real network, and evaluate the effectiveness of the method.

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