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PathKatana: Accurate Available Bandwidth Estimation for High-Speed Networks Using Packet Train Consisting Only of Large-Sized Packets

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ABSTRACT This paper proposes PathKatana, a method for accurately and stably estimating the available bandwidth of high-speed networks using packet train consisting of large-sized packets close to the MTU (Maximum Transmission Unit). Active end-to-end available bandwidth estimation is often intrusive, costly, and inaccurate. However, it is extremely important for designing high-performance network systems, improving network protocols, building distributed systems, and enhancing application performance. PathKatana follows the principle of PathRefiner estimation and calculates estimated values by transmitting and receiving packets near the size of MTU, using a modified theoretical curve. By calculating the absolute delay based on the transmission and reception data of reference packets and fitting it with the modified PathQuick3 theoretical curve, PathKatana estimates the available bandwidth. When implemented on an actual device and evaluated on a 1 Gbps high-speed line, PathKatana demonstrated superior estimation accuracy compared to conventional methods. It was confirmed that PathKatana can estimate the available bandwidth of high-speed lines with high accuracy.

INDEX TERMS Available bandwidth estimation, packet train, high-speed line, high accuracy.

I. INTRODUCTION

IN RECENT years, network technique has developed rapidly, high-speed transmission technique has already become widespread, and the application of high-speed networks has deeply affected various aspects of people's work, learning, and life. Bandwidth estimation technique, one of the important research hotspots in the current network field, needs to be able to adapt to the demand of high-speed network research as the support of network management and research. Knowing the state of available bandwidth [1] allows us to assess network congestion levels and to deploy more useful Internet applications, such as streaming and cloud applications. Since available bandwidth is constantly changing, it is affected by changes in network traffic, and the final measurement results are also affected by unpredictable factors. Therefore, the realization of an accurate method of measuring available bandwidth is a challenging target and one of the research hotspots. Estimation of available bandwidth generally requires low load, low latency, high accuracy, and high stability, and it is necessary to obtain good results quickly and conveniently in various network environments, especially here for high-speed lines. Several methods [2], [3], [4], [5], [6], [7], [8], [9], [10], [11], [12] have already been proposed for estimating available bandwidth, such as using packet trains [2], to investigate available bandwidth easily and without putting a load on the network.

However, although conventional packet-train-based available bandwidth estimation methods are characterized by low load and short measurement time, they face difficulties when applied to high-speed lines due to limitations imposed by the Maximum Transmission Unit (MTU). For instance, in many networks, the MTU is typically set to 1500 bytes, restricting the maximum size of packets that can be transmitted. This limitation prevents the use of larger packets, which not only could enhance the accuracy of bandwidth estimation but also increase the measurable upper limit of available bandwidth. Consequently, these conventional methods, which transmit packets from the smallest to the largest sizes, often suffer from inaccuracies and instability, as they cannot fully utilize larger packet sizes that would better reflect congestion in high-speed networks.

Therefore, in this study, we use the estimation principle of PathRefiner [12], an available bandwidth estimation method based on packet train, and adjust the sending and receiving data packets as the premise, and propose a high-precision, highly stable available bandwidth estimation method on high-speed line, PathKatana transmits and receives packets that are close to the size of MTU, calculates the absolute delay based on the transmission and reception data of the reference packet, and fits it with the modified PathQuick3 theoretical curve to calculate the estimated value of available bandwidth.

Section II describes the conventional techniques and their issues, Section III describes the proposed method, Section IV evaluates the effectiveness of the proposed method through experiments on actual equipment, and Section V provides a summary.

The main contributions of this paper are fourfold:

(1) We discovered that when conventional available bandwidth estimation methods are applied to high-speed networks (e.g., 1 Gbps), the estimation errors and variability of results increase significantly due to constraints such as the MTU size and sensitivity to network noise. These limitations highlight the challenges of achieving accurate and stable bandwidth estimation in high-speed environments.

(2) To address these limitations, we proposed PathKatana, a novel available bandwidth estimation method that utilizes large-sized packets close to the MTU for more precise delay measurement. PathKatana also introduces the use of reference packets to recalibrate delay models, reducing noise impact and enhancing robustness in high-speed network scenarios.

(3) We conducted comprehensive experiments on a 1 Gbps testbed to evaluate PathKatana's performance against conventional methods. For the same communication overhead, PathKatana reduces estimation errors by 72.4% and variability by 62.0% compared to PathRefiner. Alternatively, to achieve the same level of accuracy and stability, PathKatana requires 52.3% less data transmission compared to existing methods.

II. CONVENTIONAL TECHNIQUES AND ITS ISSUES

This section first describes general techniques for measuring and estimating available bandwidth. Next, the principles and specific examples of estimating available bandwidth using conventional packet train techniques are described. Finally, the challenges of conventional techniques are described.

A. GENERAL TECHNIQUES FOR MEASURING AND ESTIMATING AVAILABLE BANDWIDTH

Available bandwidth is the remaining unused bandwidth after subtracting the bandwidth actual used from the line capacity [1]. The transmission path in a network consists of the multiple forwarding links from the data source to the destination. The bandwidth or capacity of a link is the maximum transmission rate of data messages over the link. Traffic flows rarely exist alone on a single path and often share the network with other traffic flows.

Techniques for measuring or estimating available bandwidth include methods measuring available bandwidth from packets passing through routers and switches, such as MRTG (Multi Router Traffic Grapher) [13], and a technique called active estimation, which sends inspection packets and estimates available bandwidth based on delay, etc. Measurement methods such as MRTG can only provide information on directly connected links of nodes, such as switches. Therefore, they are not useful when the bottleneck on the route is not known in advance, such as when the bottleneck point from end to end is unknown. In addition, in many cases, only network administrators are authorized to use MRTG, making it difficult for ordinary users to use it. As for active estimation, iperf [14] occupies a large amount of network resources (high load) and inconveniences other users. And if estimation is performed repeatedly over a long period of time, the load on the network also increases. Other than these conventional technologies, conventional packet train methods such as PathQuick3 [3], [4], pathChirp [5], and Pathload [6], [7], [8], [9] estimate the available bandwidth with low load, low latency, high accuracy, and high stability. They send only three or several more series of estimated packets consisting of UDP (User Datagram Protocol) packets. In the following, we focus on discussing the available bandwidth estimation technique of the packet train method, which estimates the available bandwidth by instantaneously congesting the network.

B. ESTIMATION PRINCIPLE OF AVAILABLE BANDWIDTH FOR PACKET TRAIN (PATHQUICK3) METHOD

The principle of estimating the available bandwidth of a packet train system is as follows.

If the transmission rate at the transmitting terminal of the packet train is less than the available bandwidth, there is no queuing delay for the estimated packets on the network path. Therefore, the reception interval of the estimated packet is equal to the transmission interval at the transmitting terminal. On the other hand, if the transmission rate exceeds the available bandwidth, queuing delays occur at the bottleneck location. As a result, the reception interval of estimated packets begin to be wider than the transmission interval at the transmitting terminal. Thus, the aforementioned investigation is conducted. The transmission rate obtained by dividing the packet size when instantaneous congestion occurs by the transmission interval is the estimated available bandwidth.

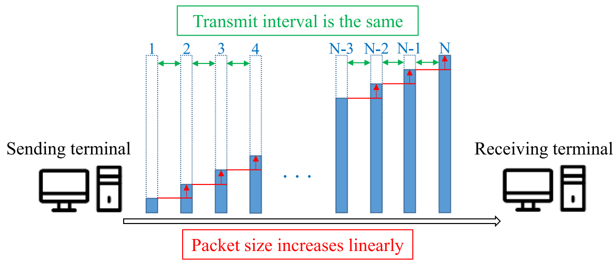

FIGURE 1. Packets sent out by PathQuick3.

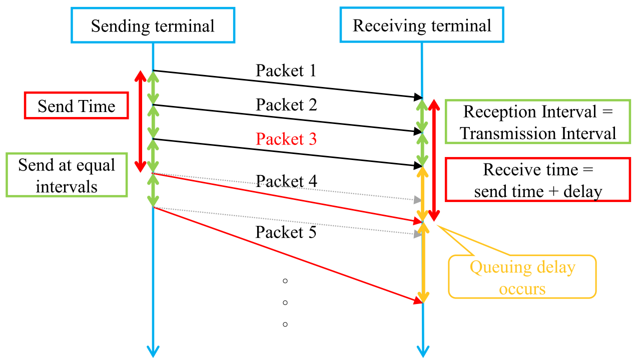

FIGURE 2. Queuing delay caused by PathQuick3.

PathQuick3 is one of packet train methods that can estimate the available bandwidth in a shorter time and with lower load than others. PathQuick3 calculates the available bandwidth as follows.

PathQuick3 first detects the delay as described in the previous section, then performs fitting and calculates the estimated value. Then, by shortening the interval between each estimated packet in the packet train, it is possible to satisfy the requirement that the estimated packets be placed at equal intervals. To achieve this, the transmission interval of each estimated packet in the packet train was equally spaced, as shown in Fig. 1. With a linear increase in packet size, varying the transmission rate for each estimated packet within a single packet train can be satisfied. The transmission rate at which queuing delays begin to occur is used as the estimated available bandwidth. As shown in Fig. 2, the estimated per-packet transmission rate exceeds the available bandwidth for the first time in packet 4. In this case, the reception interval is equal to the transmission interval because no queuing delay occurs up to the estimated packet 3. On the other hand, since the transmission rate of packet 4 exceeds the available bandwidth, queuing delays occur at bottleneck points on the network path. As a result, the reception interval becomes wider than the transmission interval. At the receiving terminal, the estimated packet for which the receive interval begins to increase is the estimated packet 4, so the transmission rate of the estimated packet 3 immediately before the estimated packet 4 is used as the estimated value of the available bandwidth.

Next, the transmission rate at which queuing delays begin to occur is found by fitting the observed queuing delays to

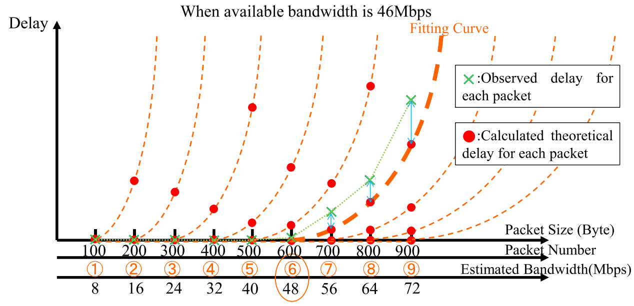

FIGURE 3. Fitting with PathQuick3 when available bandwidth is 46 Mbps.

a curve of ideal queuing delays determined for each value of available bandwidth. Each of these curves is constructed by connecting the absolute delays of individual packets under the specific corresponding bandwidth. This makes the estimates less susceptible to temporary noise and cross-traffic and allows for robust estimation. In Fig. 3, the logical delay (delay point) is depicted for each i, assuming that no delay is observed up to the i-th packet, and that queuing delay is observed starting with the i-th packet. The curve connecting the points calculated for each i (curve in Fig. 3) is called the delay point line. The logical delay is calculated by computation [3]. The curve with the smallest sum of squares of the difference between the delay point of the j-th packet and each point of the delay observed in the j-th packet (marked with X in Fig. 3) on the delay curve is selected.

It has already been shown that estimation is possible when the available bandwidth is less than 100 Mbps [3].

C. MECHANISM OF AVAILABLE BANDWIDTH ESTIMATION FOR HIGH-SPEED LINES IN PATHREFINER

When estimating available bandwidth on high-speed lines, several challenges arise, one of which is the timing inaccuracies caused by certain network card features. For example, using Interrupt Coalescing (IC) on the NIC for packets larger than the MTU can cause inaccurate packet timing on the receiving end, negatively impacting the bandwidth estimation process [9], [15], [16], [17]. This is particularly problematic when using normal PCs for measurement, as opposed to specialized hardware designed to avoid such issues.

To address these challenges, PathRefiner employs a method that bypasses the MTU limitations by concatenating multiple packets to create a virtual large packet group (virtual packet). The transmission interval between packet groups is kept constant, and the packet size of each group is linearly increased while concatenating packets of the same concatenation number C in the group. Assume that all packet sizes within a group are the same. As shown in Fig. 4, the estimated transmission rate per packet exceeds the available bandwidth for the first time in packet 4-3 of group 4. In this case, since no queuing delay occurs up to group 3, the receive interval is equal to the transmission interval. On the other hand, since the transmission rate of Group 4 exceeds the available bandwidth, queuing delays

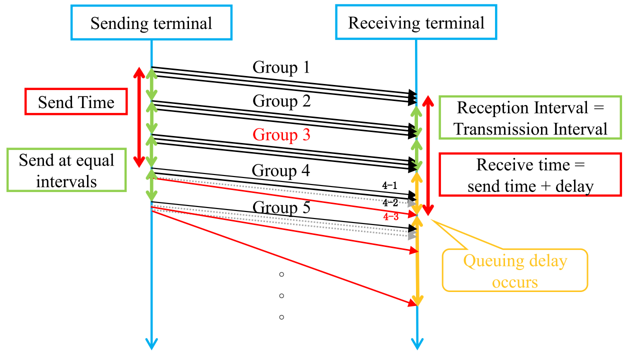

FIGURE 4. Sequence diagram of packet transmission and reception in PathRefiner (for $C = 3$).

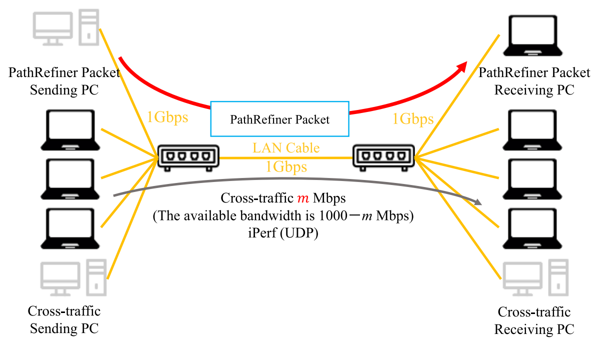

FIGURE 5. Evaluation model and parameters for available bandwidth estimation.

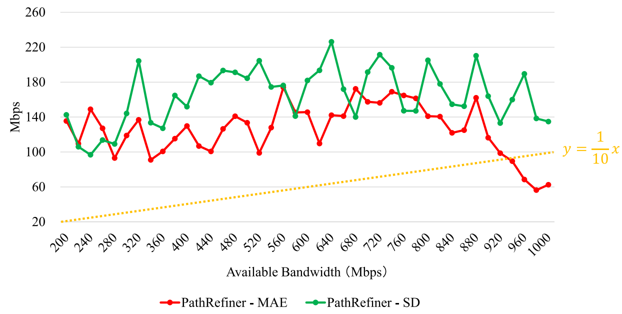

FIGURE 6. Results of preliminary experiments.

occur at the routers and switches on the network path. As a result, the receive interval becomes larger than the send interval. At the receiving terminal, the estimated group where the receive interval begins to expand is group 4, so the transmission rate of the estimated group 3 immediately before group 4 is used as the estimated value of the available bandwidth. When a high-speed line is used, the upper limit of estimation can also be changed by changing the number of concatenation C.

D. CHALLENGES OF CONVENTIONAL METHODS

The conventional method faces several fundamental issues. Firstly, PathRefiner has inherent limitations in accurately estimating the available bandwidth, especially under varying network conditions. This method struggles to maintain precision and stability when the available bandwidth is low, indicating a significant limitation in its applicability.

Secondly, PathRefiner's reliance on packet train for bandwidth estimation makes it susceptible to cross-traffic interference. This dependency can lead to highly variable results, particularly in environments with unpredictable or heavy cross-traffic, thus undermining the reliability of the estimates.

To substantiate these challenges, we conducted preliminary experiments. Fig. 5 shows the equipment and connection configuration for the evaluation experiment. We estimated the available bandwidth by sending packet trains from the PathRefiner's sending PC to the PathRefiner's receiving PC while other users were communicating. Cross-traffic is sent using iperf from the cross-traffic sending PC to the cross-traffic receiving PC, sending a UDP stream with a specified transmission rate. The test network was configured using Gig Ethernet lines and Gig Ethernet switches to create various available bandwidths within a 1 Gbps line capacity. In the experiment, the expected available bandwidth was 200-1000 Mbps for a 1 Gbps physical line by changing the cross-traffic. While varying the cross-traffic rate m from 0 Mbps to 800 Mbps in 20 Mbps increments, packet trains are sent, and the estimated values are recorded to calculate the mean absolute error (MAE) and standard deviation (SD). The true value of the available bandwidth is expressed by (1).

$$True\ Value = Line\ Capacity - m \tag{1}$$

The mean absolute error is defined by (2) and the standard deviation by (3). The n in (2), (3) is the number of times estimated.

$$MAE = \frac{1}{n}\sum_{i=1}^{n}(Estimate\ Value_i - True\ Value_i) \tag{2}$$

$$SD = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(MAE_i - \overline{MAE}\right)} \tag{3}$$

As shown in Fig. 6, for each scale value in horizontal axis, 100 repetitive estimation experiments are conducted using PathRefiner. Results of each experiment are recorded, mean absolute errors and standard deviations between estimated value and actual bandwidth are calculated. For the 100 results in each scale value, the mean absolute error is not only very large, but the standard deviation is also large, far exceeding 10% of the actual available bandwidth, especially when the available bandwidth is small; PathRefiner can handle estimating the available bandwidth of 1 Gbps high speed line, but it cannot provide higher accuracy and stability. Therefore, the goal of this study is to develop a new method that can estimate with smaller errors and smaller error fluctuation without increasing estimation cost.

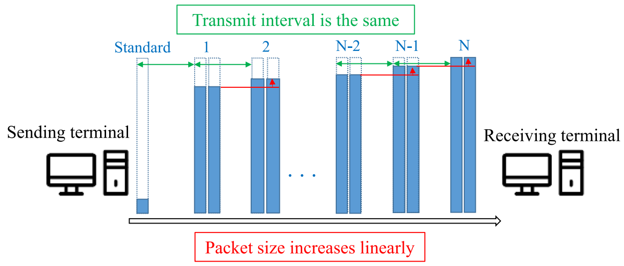

FIGURE 7. Sending packets with PathKatana (C=2).

III. PROPOSAL OF PATHKATANA

This paper proposes PathKatana, a bandwidth estimation method that solves the problem of accurate estimation of available bandwidths even in high-speed lines. Observe actual delays by sending and receiving a packet train consisting only of large packets, and fit a theoretical curve modified with a reference packet using those actual delays. The following is a description of this method.

A. PACKET TRAIN CONSISTING ONLY OF LARGE SIZE PACKETS

In PathKatana, the estimation is achieved by sending and receiving large size packets only in the vicinity of the MTU. In the previous section, we described how PathQuick3 obtains the delay of each packet on the receive side and estimates the available bandwidth by fitting a theoretical curve. The theoretical curve has two properties: one is that it is always zero before the delay occurs, and the other is that after the delay, the curvature of the curve increases as the delay increases with packet size. The method used for curve fitting calculates the sum of squares of the difference between the observed and theoretical values and selects the minimum value to qualify the bandwidth corresponding to the curve as a usable bandwidth. Since the delay values are monotonically increasing, this means that in the sum of squares, the data at the end of the curve has more weight and has a greater influence on the final data.

Taking advantage of this property, PathKatana proposes a way to improve the accuracy of the results by exploiting the fact that big packets of data have higher weights. As shown in Fig. 7, similar to PathRefiner, PathKatana concatenates multiple packets to form a virtual large packet group (virtual packet), effectively simulating a single large packet for estimation purposes, but the packet train transmits large packets very close to the MTU directly after transmitting the first reference packet. Subsequent packets gradually increase in size until finally the MTU is reached.

The reasons for only using large packets are multifaceted and primarily revolve around improving the accuracy and stability of the bandwidth estimation. First, using large packets enhances accuracy. Small packets tend to have higher relative processing times and queuing delays in network devices, which can introduce significant variability and inaccuracies in delay measurements. These smaller packets may not adequately represent the actual conditions of the network, leading to less reliable data. In contrast, large packets experience more substantial delays as they traverse the network, making the measurement of these delays more distinct and accurate. This distinctness helps in obtaining more precise delay measurements, which are crucial for accurate bandwidth estimation.

Second, using large packets improves the stability of the estimation process. Network traffic is inherently variable, with fluctuations that can significantly affect smaller packets. These fluctuations can introduce noise and instability into the estimation process, making it difficult to obtain consistent results. Large packets, however, are less susceptible to these fluctuations due to their size. They provide a more stable signal amidst the noise of network traffic variations, leading to more reliable and consistent estimation results.

Moreover, large packets help in better utilizing the property of the theoretical curve fitting method used in PathKatana. Since the curve fitting process relies on the sum of squares of the differences between observed and theoretical delay values, the data at the end of the curve (which corresponds to the larger packets) has more weight and influences the final estimation more significantly. By focusing on large packets, PathKatana leverages this aspect to enhance the precision of the bandwidth estimation. The higher weight given to the delay measurements of large packets ensures that the final estimated bandwidth is more accurate and reflective of the actual network conditions.

PathKatana achieves a computational complexity similar to PathQuick3 and PathRefiner, primarily arising from packet transmission and reception, delay calculation, and fitting of the theoretical curves. Assuming N packet groups are sent and received, PathKatana processes these packets with a complexity of $O(N)$, as each packet group's delay needs to be recorded. For the curve fitting process, PathKatana compares the delays of N packet groups against M theoretical curves, each corresponding to different available bandwidths, resulting in a complexity of $O(M \times N)$. Additionally, PathKatana employs a least-squares method to calculate the fitting error, adding another $O(N)$ step. Thus, the overall computational complexity of PathKatana is $O(M \times N)$, matching that of PathQuick3 and PathRefiner. However, PathKatana introduces advanced features such as delay recalibration and optimized curve fitting for large-sized packets, which, while slightly increasing computational effort, significantly improve estimation accuracy and stability in high-speed network environments.

B. DELAY ASSESSMENT WITH REFERENCE PACKET PAIR

PathKatana compensates the delay of each packet with a reference packet. Since the first packet in PathKatana's packet train is a very large packet, it is very likely to have a delay when it is transmitted, which means that the calculated delay for the second packet will be a relative delay rather than an absolute delay. A relative delay is the difference

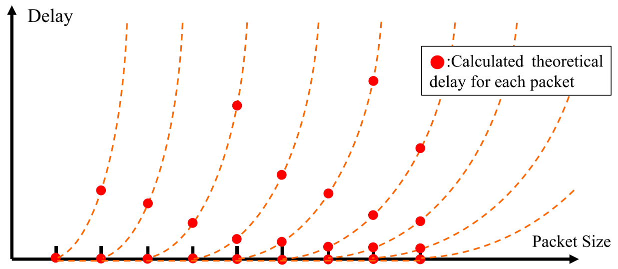

FIGURE 8. Theoretical curve for PathQuick3.

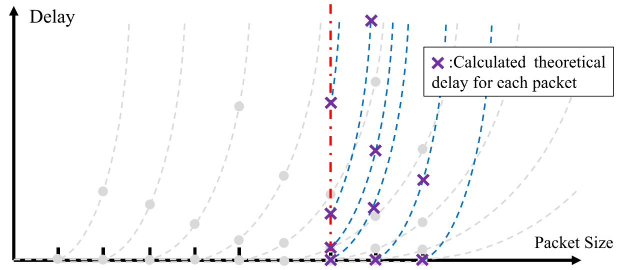

FIGURE 9. Theoretical curves for PathKatana.

in delay between a packet and the first packet in the train, whereas an absolute delay is the actual delay experienced by the packet over the network. Since the theoretical model used in PathKatana requires absolute delays for accurate fitting of the curve, a key step is to convert these relative delays into absolute delays.

To achieve this conversion, PathKatana sends a very small reference packet before the main packet train to set a baseline delay. This reference packet is almost unaffected by network congestion and size-related delays, allowing it to capture the network's inherent baseline delay accurately. The absolute delay for each large packet in the train is then calculated by subtracting this baseline delay from the measured delay, ensuring that all subsequent delay measurements accurately represent the actual network conditions. This step is crucial, as it allows PathKatana to account for the distortion caused by the initial large packet, resulting in more accurate curve fitting.

Furthermore, Fig. 8 shows the theoretical curve for PathQuick3, where each curve corresponds to a different available bandwidth. Each of these curves is constructed by connecting the absolute delays of individual packets under the specific corresponding bandwidth. In PathQuick3, the theoretical model is built upon the assumption that small packets are included in the transmission, which helps in determining the delays at various packet sizes. However, PathKatana never actually sends or receives these small packets beyond the initial reference packet. Instead, it relies on large packets for the majority of the transmission. This shift necessitates a modification in the approach to constructing the theoretical curves used for delay measurement and bandwidth estimation.

As depicted in Fig. 9, even though PathKatana uses large packets, it still needs to account for the theoretical delay points initially represented by small packets in PathQuick3. Specifically, the horizontal coordinate of the theoretical curve's starting point aligns with the baseline delay measured by the reference packet. The vertical coordinate corresponds to the delays caused by the first data packet in the packet train at each available bandwidth level. This adjustment allows PathKatana's theoretical model to accurately reflect the delays of large packets without being skewed by the absence of small packets.

To further refine the model, PathKatana recalibrates the curve fitting process based on the behavior of large packets. The delay profile of large packets differs significantly from that of small packets, so the fitting process must account for this by adapting the curve accordingly. The recalibration ensures that the theoretical model remains precise, and that the bandwidth estimation accurately captures the characteristics of high-speed networks.

By compensating for the relative delays with an initial reference packet and adapting the theoretical model to fit the characteristics of large packets, PathKatana enhances the accuracy and reliability of its bandwidth estimation. This method not only corrects for the inherent delays of large packets but also maintains the integrity of the theoretical model used for curve fitting. As a result, PathKatana can provide a more accurate estimation of available bandwidth in high-speed networks, overcoming the limitations of previous methods that relied heavily on small packets and relative delay measurements.

In summary, the strategy of using a small reference packet in PathKatana is key to obtaining accurate absolute delay measurements. Combined with the recalibration of the theoretical model to fit large packet delays, PathKatana ensures precise and reliable bandwidth estimation, offering a significant advancement over prior methods by effectively addressing the challenges posed by relative delays and the absence of small packets.

C. ACCURACY CHARACTERISTICS COMPARISON

PathQuick3, PathRefiner, and PathKatana differ in their approaches to packet size, estimation methods, handling of MTU limitations, and suitability for network speeds. PathQuick3 uses a range of packet sizes from small to large, fitting theoretical curves based on packet delays, but it is constrained by the MTU, limiting its accuracy and measurable range in high-speed networks. PathRefiner improves on this limitation primarily by increasing the measurable upper limit of available bandwidth. It does this by concatenating multiple packets to form a virtual large packet group, effectively bypassing the MTU constraint and allowing for more accurate measurement in high-speed networks (1 Gbps). PathKatana further optimizes this by directly transmitting large packets close to the MTU size to improve both accuracy and stability, focusing on minimizing

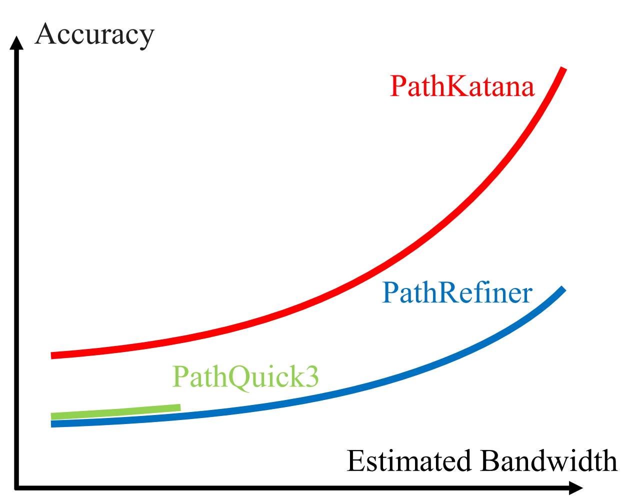

FIGURE 10. Comparison of the accuracy characteristics of the three methods.

noise and enhancing precision in Gbps-level bandwidth estimation.

Fig. 10 illustrates the differences in measurement accuracy among PathQuick3, PathRefiner, and PathKatana under various bandwidth conditions. In the case of PathQuick3, at lower bandwidths, network fluctuations and noise are more pronounced, causing greater measurement errors. While the accuracy of PathQuick3 improves as the bandwidth increases and the impact of noise and fluctuations decreases, it is ultimately limited by the MTU size. This limitation prevents the use of sufficiently large packets to measure available bandwidth accurately in high-bandwidth conditions, resulting in an inability to properly estimate larger bandwidths. PathRefiner addresses this limitation by concatenating small packets to form virtual large packets, effectively overcoming the MTU restriction and increasing the upper limit of measurable bandwidth. At lower bandwidths, the accuracy of PathRefiner is similar to that of PathQuick3. This approach allows PathRefiner to measure a broader range of bandwidths compared to PathQuick3. PathKatana, like PathRefiner, also concatenates packets to form virtual large packets, but it emphasizes the use of packets closer to the MTU size. This design choice minimizes the influence of noise and network fluctuations on measurement, significantly enhancing accuracy in high-bandwidth environments. Furthermore, PathKatana's approach improves the accuracy of the fitted curve used for bandwidth estimation, as larger packets provide a more stable and precise delay measurement. Consequently, PathKatana becomes the most accurate method among the three.

IV. EVALUATION EXPERIMENTS USING ACTUAL EQUIPMENT ON HIGH-SPEED LINES

A. EVALUATION MODEL AND EXPERIMENTAL STRUCTURE

Using actual equipment, an actual experiment is conducted to demonstrate that the proposed available bandwidth estimation method is highly accurate for high-speed lines.

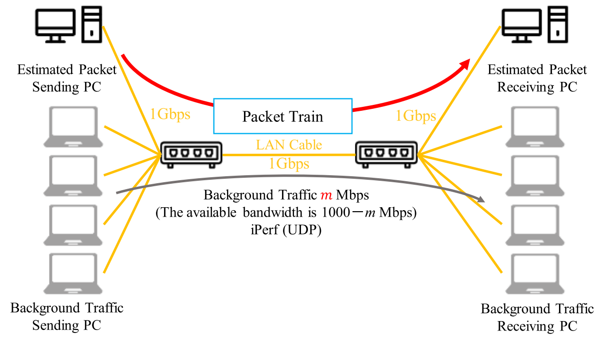

FIGURE 11. Evaluation model for available bandwidth estimation.

TABLE 1. Summary of experimental devices and parameters.

Experimental PC	HP Pavilion 15-eh1000 / Lenovo ideapad / HP EliteDesk 800 G2 SFF
Operating system	Windows
Experimental switch	Netgear 1G SW
iperf version	iperf-2.0.9
Line capacity	1 Gbps
Transmit interval	0.1 ms
Stand packet size	32Byte
The number of concatenates C	9

Fig. 11 shows the equipment and connection configuration for the evaluation experiment. The available bandwidth was estimated by sending packet trains from PathKatana's sending PC to PathKatana's receiving PC while other users were communicating over the network. Cross-traffic is sent using iperf from the cross-traffic sending PC to the cross-traffic receiving PC, sending a UDP stream with a specified transmission rate. The test network was configured using 1 Gbps class line and 1 Gbps class switches to create various available bandwidths within a 1 Gbps line capacity. Due to the availability of experimental equipment, we set the range of available bandwidth from 200 to 1000 Mbps, which is a high communication speed for our estimation. For this purpose, the communication speed of the cross-traffic m was varied from 0 Mbps to 800 Mbps in 20 Mbps increments. With these 41 patterns, we sent PathKatana packet trains and recorded the estimate values 100 times to calculate the mean absolute error MAE and standard deviation SD. Under different data amounts, nine experiments were conducted on PathKatana, and three experiments were conducted on PathRefiner.

In addition, the experimental equipment and parameters are shown in Table 1. The packet transmission interval is 0.1 ms, which is the limit for using a normal PC. Therefore,

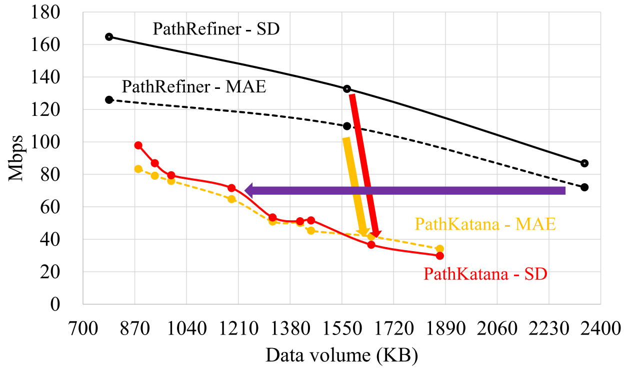

FIGURE 12. Estimation results.

to estimate in a 1 Gbps high-speed line, a virtual packet size of at least 12500 Bytes is required. To keep a single packet under an MTU, the number of concatenations C was set to 9. Since the difference in the number of packet groups and packet increments will cause changes in the overall data volume of the packet tran, the overall data volume is used to evaluate the average absolute error and standard deviation.

B. EVALUATION RESULTS

As described below, the experiment results prove that the estimation of available bandwidth was highly accurate and stable even for high-speed lines. Although the current evaluation focuses on a 1 Gbps network, the fundamental principles underlying the estimation are applicable to other Gbps-level networks as well. Fig. 12 shows the estimation results of PathKatana and PathRefiner. For the same amount of data, PathKatana achieves better estimation accuracy than the conventional method: For 1600KB data volume, the MAE reduced by 72.4% and SD reduced by 62.0%. At the same accuracy, PathKatana requires less data than the previous method: Data volume reduced by 52.3% when MAE and SD are around 80 Mbps.

V. CONCLUSION AND FUTURE WORK

We propose PathKatana, a method for estimating available bandwidth with low load, low latency, high accuracy, and high stability for high-speed lines such as 1 Gbps. PathKatana follows the estimation principle of PathRefiner and calculates the estimated value using a modified theoretical curve by sending and receiving packets that are close to the size of MTU.

To demonstrate that PathKatana can estimate with high accuracy on high-speed lines, we evaluated its MAE and SD on a 1 Gbps line using actual equipment. For the same amount of data, PathKatana provides better estimation accuracy than the conventional method. Therefore, it is proved that PathKatana can estimate available bandwidth with high accuracy on a 1 Gbps line. The design of PathKatana does not impose an upper limit on the bandwidth that can be estimated. Therefore, we expect PathKatana to achieve better evaluation results than existing methods even for high-speed networks exceeding 1 Gbps, such as 10 Gbps. However, experimental evaluation on networks exceeding 1 Gbps remains as future work.

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