A Novel Method for Estimating the Variable and Constant Components of One-Way Delays Without Using the Synchronized Clocks

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***Abstract*—One-way delay monitoring is necessary for the time-sensitive media streaming. The conventional methods of one-way delay measurement require the clocks used at both the source and sink nodes of a path have to be synchronized. Clock synchronization can be performed either through GPS or NTP-based methods. Both approaches bear certain limitations. This paper describes a novel method of estimating the variable and constant components of one-way delays without requiring the local clocks at the end nodes to be synchronized. This method requires a sequence of probing packet batches to be sent from a source to a sink along a fixed one-way path. The timestamps of sending and receiving the packets at the source and the sink are recorded with respect to the local clocks. The variable and constant components of one-way delays can be estimated based on carefully crafting the relationship between the timestamps measured with respect to local clocks. The variable delay component is estimated based on the difference between the inter-arrival times between batches that are measured at the source and the sink, respectively. The constant delay component offset by the clock skew can then be estimated by making use of the estimated values of the variable delay component and the timestamps measured locally at the source and the sink. A novel concept of nominal service duration for a packet batch is introduced in modeling the one-way delays. The introduction of the nominal service duration makes this estimation method to be able to estimate the variable component of one-way delays in the existence of cross traffic. Without the knowledge of the offset of the local clocks at the source and the sink, this estimation method can only estimate the constant delay component up to the offset value of the actual constant delay.**

***Index Terms*—One-Way Delay, Propagation Delay, Queueing Delay, Clock Synchronization, Clock Offset**

I. Introduction

Network delay is an important network performance metric which strongly affects the performance of network routing, flow control, and network media streaming services, such as the real-time audio and video streaming services [1]. In many applications, delay monitoring has to be performed on a regular basis in order to verify the compliance to delay constraints. The one-way delays are more useful than the round-trip delays for applications whose performance is dependent on one-way delays, *e.g.*, FTP and Video on Demand (VoD). Estimation of one-way delay between a pair of sender and receiver is an important issue in computer networks. Monitoring the one-way delays is especially necessary for the time-sensitive media streaming. When the function of an application relies on the live feed of a data stream, the quality-of-service (QoS) received by the application running at the sink of the data stream is sensitive to the one-way delays from the source to the sink of the data stream.

An one-way delay from a source to a sink is the time duration between when a probing packet is sent at the source and when it is received at the sink. An one-way delay consists of a constant delay component and a variable delay components. The variable component includes the cumulative queuing delays and the cumulative processing delays along an one-way path. The constant component includes the propagation delay along an one-way path. The accurate estimations of the one-way variable delays can be used to aid a sender to adjust its sending rate in TCP [2] because the queuing delays have been commonly used to infer the congestion along the path. Thus, the method of estimating the constant and variable components of one-way delays is useful for a sender to understand the congestion status of an one-way path.

Measuring the one-way delays is simple when the clocks used at a pair of source and sink are perfectly synchronized. However, this simple measurement method can not be applied to the cases when offsetting clocks (with a constant difference between the readings on the two clocks) or drifting clocks (with unknown drifting rates) are used at the pair of source and sink. Even though two clocks can be made synchronized by adopting the clock synchronization procedures, but many such procedures have their limited applicability. For example, Global Positioning Systems (GPS) can accurately synchronize the clocks used at multiple network nodes. However, GPS devices have not been densely deployed in computer networks, nor can be deployed indoors or at secured nodes. The Network Time Protocol (NTP) [3], [4] is the standard for synchronizing clocks in the Internet. NTP measures round-trip delays and uses a halving procedure to estimate the clock offsets. The NTP based clock synchronization procedures achieve a good accuracy for symmetric delays. The symmetric delays are only made possible when the probing packets take the same round-trip route with the same traffic loads and QoS configurations in both directions. When the forward and backward one-way delays along a round-trip route are different, the one-way delays cannot be accurately estimated by halving the round-trip delays. The asymmetric forward and backward one-way delays are caused by two facts: the asymmetric round-trip routes in current Internet [5], and the asymmetric queuing delays on the two one-way paths even when a round-trip route is symmetric.

This paper describes a novel method of estimating the variable delay component and the constant delay component along an one-way path without using GPS or NTP. A sequence of packet batches are sent from a source to a sink. The inter-arrival times between batches are measured at the source, and the time spans of batches are measured at the sink. Hence, only the local clocks at the source and the sink are used without requiring them to be synchronized. Then, the sequence of the difference between the time span and the inter-arrival time of a batch is derived to estimate the one-way delays experienced by the first packet in each batch. This method can accurately estimate the one-way variable delays in the existence of any kind of cross traffic and without requiring the synchronized clocks at the source and at the sink. The accurate measurement of the one-way constant delay require the clocks at the source and at the sink to be synchronized. When the local clocks are unsynchronized, this method can only estimate the one-way constant delay offsetted by the clock skew. The offsetted estimation of the one-way constant delay can still be used in judging the deadline observance in real-time transmissions.

This paper is organized into the following sections. The related work is described in Section II. The method for estimating the variable and constant delay components of one-way delays is described in Section III. The effectiveness of the estimation method is validated in Section IV. Our work is summarized in Section V.

II. Related Work

The internal links delays in a tree-like network topology have been estimated by making the multi-cast packets to traverse common links along their end-to-end paths [6]. After the one-way end-to-end delays of the multi-cast packets are measured, the delays experienced on the internal links can be derived by removing the shared delays on the common links. This method requires clock synchronization at the measurement hosts via GPS. The internal network delays have also been estimated based on the end-to-end delay measurements by solving a set of linear equations [7]. The end-to-end delay measurements can be round-trip delays or one-way delays. For round-trip delays, this method assumes that the routing is symmetric. For one-way delays, this method assumes that the clocks are synchronized. A large-scale delay measurement study [8] has been performed to capture the router-to-router delays by making use of packet traces obtained from an operational tier-1 network. In this work, the synchronized clocks are required to run on a pair of routers.

The one-way delays have been commonly estimated by halving the round-trip delays [3], [4]. The accuracy of this approaches is highly dependent on the assumptions of path symmetry of a round-trip route in the network and of the symmetric traffic load on each directional of the round-trip route. One-way link delays has also been made by separately estimating the constant and the variable parts of the one-way delays [1]. The constant one-way delay can be estimated based on the one-way single-hop measurements based on standard ICMP of NTP probes. The variable one-way link delay can be estimated based on measuring and analyzing the link between neighboring nodes. The forward and reverse one-way days have been estimated by removing the common one-way delays from the two sets of the round-trip delays measured at the source and the sink, respectively, of a TCP connection [9]. However, the accuracy of the estimation depends on the accurate estimate of an initial one-way delay. Thus, the estimation error is still similar to the accuracy of the conventional methods by estimating an one-way delay by halving a round-trip delay.

III. The Method of Estimating The One-Way Delays

In a network, a set of data streams running in the network is denoted by $\mathcal{N}$ with its cardinality $N = |\mathcal{N}|$. The data stream i ($i \in \mathcal{N}$) is delivered from a source to a sink along a fixed one-way path. Each stream sends batches of data packets from its source to its sink. The sequence of batches in data stream i is labeled by a sequence $\{1, 2, \cdots, k, \cdots\}$. A batch of packets consists of at least two packets. The possible packet losses have been ignored in the modeling. The modeling of the constant and the variable components of an one-way delay follows the alternative defition in which an one-way constant delay is treated as a sum of the one-way propagation delay and the cumulative transmission delays along an one-way path. Time measurements are performed at the source and the sink of a stream according to the local clocks. Due to the possible clock skew, the timestamps with respect to the clock on the source side are symbolized by t, and the timestamps with respect to the clock on the sink side are symbolized by T. The notations used in the modeling is shown in TABLE I.

The inter-arrival time of the batchs on the source side is expressed as $a_{i,k}^{s,\text{first}} = t_{i,k+1}^{s,\text{first}} - t_{i,k}^{s,\text{first}}$, and the inter-arrival time on the sink side is expressed as

$$a_{i,k}^{r,\text{first}} = T_{i,k+1}^{r,\text{first}} - T_{i,k}^{r,\text{first}}. \quad (1)$$

The time-stamps $T_{i,k+1}^{s,\text{first}}$ and $T_{i,k}^{s,\text{first}}$ are used as the imaginary time-stamps measured according to the local clock on the sink side, which correspond to the time-stamps $t_{i,k+1}^{s,\text{first}}$ and $t_{i,k}^{s,\text{first}}$, respectively. However, $T_{i,k+1}^{s,\text{first}}$ and $T_{i,k}^{s,\text{first}}$ can not be directly measured at the sink. Despite the clock

τ_i	the one-way end-to-end propagation delay along the path used by stream i.
$t_{i,k}^{s,\text{first}}$	the time when source starts to send the first packet in the k-th batch.
$T_{i,k}^{s,\text{first}}$	the time when the first packet of the k-th batch starts its transmission at the source with respect to the clock on the sink side.
$T_{i,k}^{r,\text{first}}$	the time when the first packet of the k-th batch is fully received at the sink.
$T_{i,k}^{r,\text{last}}$	the time when the last packet of the k-th batch is fully received at the sink.
$q_{i,k}$	the one-way cumulative queuing delay experienced by the first packet.
$w_{i,k}$	the one-way cumulative delay for the first packet in k-th batch.
$v_{i,k}$	the one-way cumulative variable delay for the first packet in k-th batch.
$f_{i,k}^{\text{first}}$	the one-way cumulative processing delay for the first packet.
$g_{i,k}^{\text{first}}$	the one-way cumulative transmission delay for the first packet.
$\tilde{c}_{i,k}$	the one-way constant delay offsetted by a clock skew seen by the first packet in the k-th batch.
$S_{i,k}^{\text{nominal}}$	the nominal service duration of the k-th batch.
$a_{i,k}^{s,\text{first}}$	the time duration between transmitting the first packets in the $(k+1)$-th and the k-th batches on the source side.
$a_{i,k}^{r,\text{first}}$	the time duration between the arrival timestamps of the last packets in the $(k+1)$-th and the k-th batches on the sink side.

TABLE I: The notations used in modeling the i-th stream.

skew, a time duration is indifferent to where the duration is measured. Thus, we have that

$$a_{i,k}^{s,\text{first}} = T_{i,k+1}^{s,\text{first}} - T_{i,k}^{s,\text{first}} = t_{i,k+1}^{s,\text{first}} - t_{i,k}^{s,\text{first}}. \quad (2)$$

The nominal service duration of the k-th batch is defined as

$$S_{i,k}^{\text{nominal}} = T_{i,k}^{r,\text{last}} - T_{i,k}^{r,\text{first}}. \quad (3)$$

It is noteworthy that the nominal service duration of a batch may includes the time used for serving packets in other streams and/or the idle time at the intermediate routers (ref. Fig. 1).

A. Estimating the One-way Cumulative Variable Delays

The one-way cumulative variable delay experienced by the first packet in the k-th batch includes the one-way cumulative queueing, transmission, and processing delays and is expressed as

$$v_{i,k} = q_{i,k} + f_{i,k}^{\text{first}}. \quad (4)$$

The one-way delay experienced by the first packet in the k-th batch is the sum of the one-way constant and cumulative variable delays, and it is expressed as

$$\begin{aligned} w_{i,k} &= T_{i,k}^{r,\text{first}} - T_{i,k}^{s,\text{first}} \\ &= \tau_i + g_{i,k}^{\text{first}} + v_{i,k} \\ &= \tau_i + g_{i,k}^{\text{first}} + q_{i,k} + f_{i,k}^{\text{first}}. \quad (5) \end{aligned}$$

Based on expressions (1), (2), and (5), we have the recursion of

$$w_{i,k+1} = w_{i,k} + (a_{i,k}^{r,\text{first}} - a_{i,k}^{s,\text{first}}). \quad (6)$$

Based on Eq. (4), (5), and (6), we further have that $v_{i,k+1} = v_{i,k} + (a_{i,k}^{r,\text{first}} - a_{i,k}^{s,\text{first}})$. This recursion can be used to estimate the one-way cumulative variable delays experienced by the first packets in the batches. When $a_{i,k}^{r,\text{first}} = a_{i,k}^{s,\text{first}}$, we have that $v_{i,k+1} = v_{i,k}$. This means that the first packet in the k-th batch has experienced the same amount of cumulative queuing delays along the one-way path. Among the cases of adjacent batchs experiencing the same amount of cumulative queuing delays, one possible situation is that the first packets in two adjacent batchs experience a zero cumulative queuing delay. When the value of $v_{i,k}$ is to be estimated, we denote batch k_0 ($k_0 < k$) as the most recent batch which yields $a_{i,k_\bullet}^{r,\text{first}} = a_{i,k_\bullet}^{s,\text{first}}$. Hence, the value of $v_{i,k}$ can be expressed as

$$v_{i,k} = v_{i,k_\bullet} + \sum_{k_\bullet \le j < k} (a_{i,j}^{r,\text{first}} - a_{i,j}^{s,\text{first}}).$$

If $v_{i,k_\bullet} = 0$, then the one-way cumulative variable delay can be estimated by

$$v_{i,k} = \sum_{k_\bullet \le j < k} (a_{i,j}^{r,\text{first}} - a_{i,j}^{s,\text{first}}). \quad (7)$$

A heuristic that $v_{i,k_\bullet} = 0$ when $a_{i,k_\bullet}^{r,\text{first}} = a_{i,k_\bullet}^{s,\text{first}}$ is assumed in this estimation. This assumption is the only factor that affects the accuracy of the estimation. The values of $v_{i,k}$ can be estimated under unsynchronized clocks.

B. Estimating the One-Way Constant Delay

The estimated values of the one-way cumulative variable delays can be used to estimate the one-way constant delay offsetted by the clock skew. Here, we only consider the case of offsetting clocks, the clock skew between the local clocks is expressed as $\delta_i = T_{i,k}^{s,\text{first}} - t_{i,k}^{s,\text{first}}$. Based on Eqs. (3) and (5), we have that

$$S_{i,k}^{\text{nominal}} = T_{i,k}^{r,\text{last}} - [T_{i,k}^{s,\text{first}} + (q_{i,k} + \tau_i + f_{i,k}^{\text{first}} + g_{i,k}^{\text{first}})].$$

Based on Eq. (2), we further have that

$$\begin{aligned} S_{i,k}^{\text{nominal}} - a_{i,k}^{s,\text{first}} &= T_{i,k}^{r,\text{last}} - T_{i,k+1}^{s,\text{first}} \\ &\quad -(q_{i,k} + \tau_i + f_{i,k}^{\text{first}} + g_{i,k}^{\text{first}}). \end{aligned}$$

However, $T_{i,k+1}^{s,\text{first}}$ can not be directly measured on the sink side, and we also know that $T_{i,k+1}^{s,\text{first}} = t_{i,k+1}^{s,\text{first}} + \delta_i$ in which $t_{i,k+1}^{s,\text{first}}$ can be directly measured on the source side. Thus, we have that

$$\begin{aligned} S_{i,k}^{\text{nominal}} - a_{i,k}^{s,\text{first}} &= T_{i,k}^{r,\text{last}} - (t_{i,k+1}^{s,\text{first}} + \delta_i) \\ &\quad -(v_{i,k} + \tau_i + g_{i,k}^{\text{first}}). \end{aligned}$$

Fig. 1: Illustration of the timelines of the nominal batches at the sink of stream i.

Thus, the one-way constant delay offsetted by the clock skew is estimated as

$$\begin{aligned}\tilde{c}_{i,k} &= (\tau_i + g_{i,k}^{\text{first}}) + \delta_i \\ &= (T_{i,k}^{r,\text{last}} - t_{i,k+1}^{s,\text{first}}) - (S_{i,k}^{\text{nominal}} - a_{i,k}^{s,\text{first}}) - v_{i,k}.\end{aligned}$$

Without knowing the value of δ_i, we can not estimate the actual value of τ_i. Meanwhile, the one-way constant delay offsetted by the clock skew can still be used to allow the sink to infer the total one-way delay experienced by a packet batch. For example, the first packet in the k-th batch is sent at the source at $t_{i,k}^{s,\text{first}}$ according to the local clock at the source, and the last packet in the k-th batch is received at the sink at $t_{i,k}^{s,\text{first}} + [\delta_i + (\tau_i + g_{i,k}^{\text{first}}) + v_{i,k} + S_{i,k}^{\text{nominal}}]$ according to the local clock at the sink. Then, the total one-way delay of the k-th batch can be expressed as $[\delta_i + (\tau_i + g_{i,k}^{\text{first}}) + v_{i,k} + S_{i,k}^{\text{nominal}}]$.

IV. Validation to the Method of Estimating the variable and constant Components of One-Way Delays

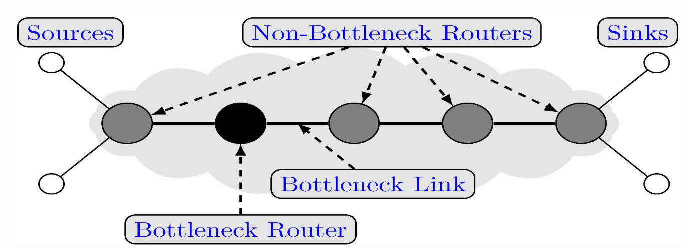


Fig. 2: The network topology used in the numerical analysis.

The effectiveness of the method of estimating the variable and constant components of one-way delays has been validated using network simulations. A simple network topology shown in Fig. 2 is used in the evaluation. The DropTail queuing policy is adopted at all the routers. The propagation delays on all links are 10 ms. The bandwidths of an access link, a non-bottleneck link, and a bottleneck link are 50 Mbps, 30 Mbps (or 3.75 MBytes/s), and 25 Mbps (or 3.125 MBytes/s), respectively. Two streams are used to deliver packets from their sources to their corresponding sinks. One stream delivers the probing traffic, and the other four streams are used to deliver cross traffic along the same path as the probing traffic. The probing traffic consists of a sequence of packet batches with each batch is labeled by a batch number which allows the sink to identify the first and the last packets in a batch. Each batch consists of at least 2 packets, and timing is recorded only on the first and the last packets in a batch. The number of packets in a batch has no relationship to the accuracy of the estimation. The modeling of a batch as a sequence of multiple packets allows the estimation continue to function when the probe packets are delivered out-of-the-order or lost. In either case, a batch with out-of-the-order or lost packets can be merged into a super batch with its immediately prior and next batches.

	$\mathbb{E}[a^s]$ (Seconds)	$\mathbb{E}[N_P]$ (Packets)	min N_P (Packets)	Packet Size (Bytes)
Probe traffic	0.05	10	2	100
	$\mathbb{E}[a^s]$	$\mathbb{E}[N_P]$	Var$[N_P]$	Packet Size
	(Seconds)	(Packets)	(Packets^2)	(Bytes)
Cross Traffic	0.002	10	2100	1000

TABLE II: Specification of the Traffic Streams.

The arrival pattern of packet batches in the probing traffic follows a *Poisson* process, and the number of packets in a batch follows an exponential distribution. A stream of cross traffic also sends packet batches with the batch arrivals following a *Poisson* process and the batch size following a Normal distribution. The adoption of a Normal distribution of the batch size of a cross traffic tries to mimic the *Gaussian* traffic pattern seen at the major aggregation routers where a large number of flows are multiplexed [10], [11]. The evaluation based on other traffic patterns of the cross traffic has also been performed in our study. More accurate estimation is obtained under the relatively smooth cross traffic than under bursty cross traffic. We choose to present the estimation results under the bursty cross traffic. The traffic patterns of the traffic flows are shown in TABLE II. $\mathbb{E}[a^s]$ represents the average inter-arrival time between batches, $\mathbb{E}[N_P]$ represents the average batch size in packets, $\mathrm{Var}[N_P]$ represents the variance of the batch size in unit of square packets for the Normal distribution, and $\min N_P$ represents the minimum batch size in packets.

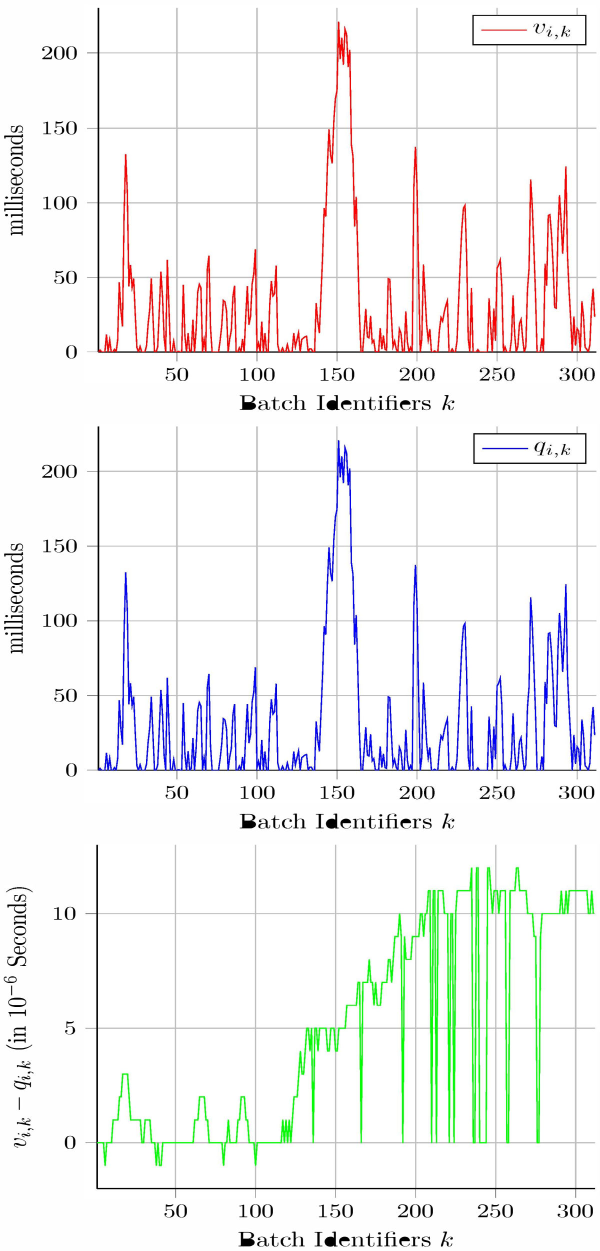
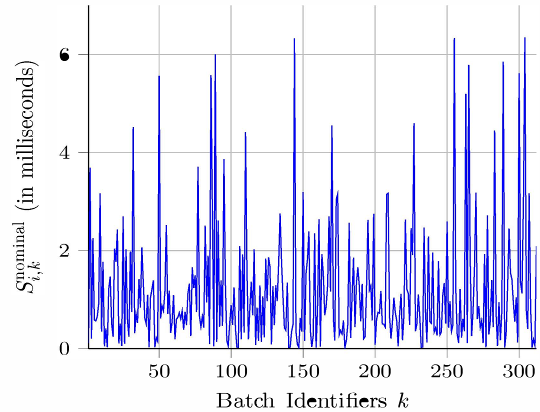


Fig. 3: Effectiveness on Estimating the One-Way Cumulative Variable Delays.

The effectiveness of the method of estimating the variable and constant components of one-way delays is demonstrated through the comparison of the measured and the estimated values. We have monitored the actual one-way cumulative queueing delays for the first packet in each batch. As shown in Fig. 3, the measured and the estimated values of the variable one-way delays for the same batch are very close to each other with the estimation error being restricted within a few microseconds. The estimated values of the constant one-way delay for each batch is shown in Fig. 4(b). For demonstration purposes, the clock skew between the local clocks at the source and the sink has been made to be zero. The estimated values of the constant one-way delay shown in Fig. 4(b) stay close to the actual one-way constant delay whose value is 60.14 milliseconds. The estimation error is bounded within 10 microseconds.



(a) The Norminal Serivce Time

(b) The Estimated Constant Delay

Fig. 4: Illustration of the estimations the per-batch static delays. The details of the estimation errors are zoomed in the inset graph.

V. Conclusions

This paper describes a novel method of estimating the variable and constant components of one-way delays without requiring the synchronized local clocks at the end nodes. This method requires a sequence of probing packet batches to be sent from a source to a sink along a fixed one-way path. The timestamps of sending and receiving the packets at the source and the sink are recorded with respect to the local clocks. The variable and constant components of one-way delays can be estimated based on carefully crafting the relationship between the timestamps measured with respect to local clocks. The variable delay component is estimated based on the difference between the inter-arrival times between batches that are measured at the source and the sink, respectively. The constant delay component offsetted by the clock skew can then be estimated by making use of the estimated values of the variable delay components and the timestamps measured locally at the source and the sink. A novel concept of nominal service duration for a packet batch is introduced in modeling the one-way delays. The introduction of the nominal service duration makes this estimation method to be able to estimate the variable component of one-way delays in the existence of cross traffic. Without the knowledge of the offset of the local clocks at the source and the sink, this estimation method can only estimate the constant delay component up to the offsetted value of the actual constant delay. The effectiveness of this estimation method has been evaluated by means of network simulations. The evaluation results show that both the variable delay components and the offsetted value of the constant component of one-way delays can be accurately estimated in the existence of any type of cross-traffic.

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