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One-way delay estimation without clock sychronization

Dongkeun Kim[a)] **and Jaiyong Lee**
Department of Electrical and Electronic Engineering, Yonsei University, 120–749, Seoul, Korea
a) *neurok@yonsei.ac.kr*

Abstract: One-way delay measurement requires end-to-end hosts to be synchronized in clock time on network. However, there is the relative or absolute difference between two clock times by reason of clock offset, clock skew and so on. In this paper, we present a theorem, methods and simulation results of one-way delay and clock offset estimations between end-to-end hosts. The proposed theorem is a relationship between one-way delay, one-way delay variation and round-trip time, and we show that the estimation error is mathematically smaller than a quarter of round-trip time.

Keywords: clock synchronization, one-way delay, clock offset, clock skew
Classification: Science and engineering for electronics

References

[1] D. Mills,"Improved algorithms for synchronizing computer network clocks," *IEEE/ACM Trans. Netw.*, vol. 3, no. 3, pp. 245–254, June 1995.
[2] V. Paxson,"On Calibrating Measurements of Packet Transit Times,"in *Proceedings of ACM SIGMETRICS*, June 1998.
[3] G. Almes, S. Kalidindi, and M. Zekauskas,"A One-way Delay Metric for IPPM," *RFC2679*, IETF, Sept. 1999.
[4] C. Demichelis and P. Chimento, "IP Packet Delay Variation Metric for IP Performance Metrics (IPPM)," *RFC3393*, IETF, Nov. 2000.
[5] J.-H. Choi and C. Yoo, "One-Way Delay Estimation and Its Application," *Elsevier Computer Communications*, vol. 28, no. 7, May 2005.
[6] A. Varga, OMNeT++: Discrete Event Simulation Environment. [Online] http://www.omnetpp.org
[7] S. Floyd and V. Jacobson, "Random Early Detection Gateways for Congestion Avoidance," *IEEE/ACM Trans. Netw.*, vol. 1, no. 4, pp. 397–413, Aug. 1993.

1 Introduction

One-way delay measurement requires a guarantee of clock synchronization between end-to-end hosts on network. However, the hosts have the relative or absolute difference in clock time by reason of clock offset, clock skew and clock adjustment. Although there are many other issues [1, 2], we focus on

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the clock offset and skew. This terminology follows [1, 2, 3, 4] besides its notations for convenience.

There are two kinds of estimation approaches for clock offset based on symmetry or asymmetry of one-way delays. One is used in well-known NTP protocol [1] in which each of one-way delays is a half of round-trip time (=RTT) provided the one-way delays are symmetry. The other approach including our proposal considers the fact that one-way delays are asymmetry [2, 5]. And, one-way delay variation (=jitter) only depends on the difference of RTTs because the effects of clock skew can be naturally removed [4, 5]. This relationship is used in our proposal as well.

Furthermore, our proposed theorem mathematically identifies a relationship between one-way delay, RTT and jitter, and shows that the upper bound of error is smaller than RTT/4 under a specific condition.

2 Basic definitions

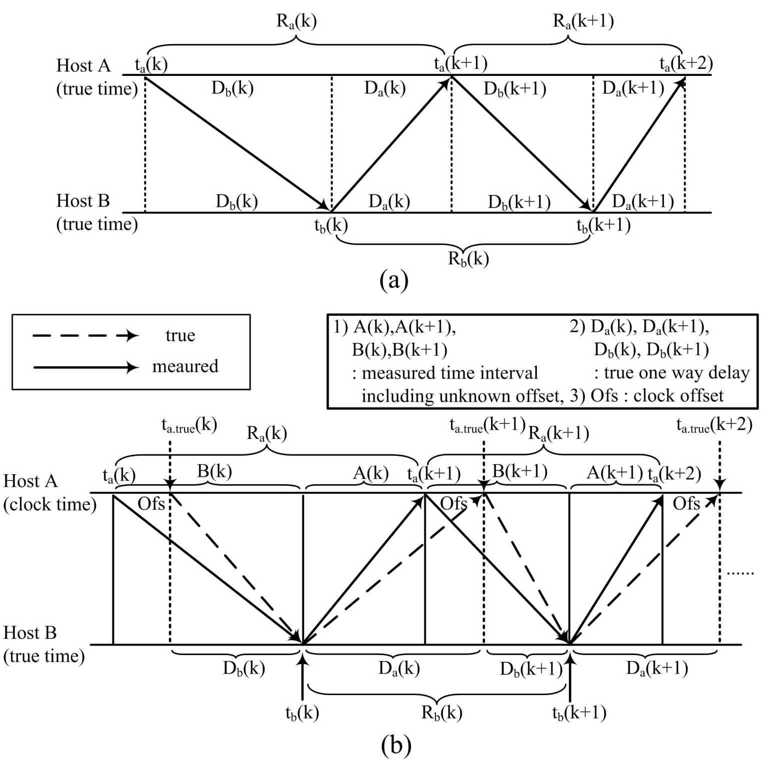

Fig. 1. (a) Synchronized case. (b) Unsynchronized case, for $\mathrm{Ofs}_a(k)$ >0.

In Fig. 1 (a), the ping-pong procedure used in this paper starts with host A sending k-th timestamp request to host B at time t_a(k). As soon as the k-th packet is received at the host B at t_b(k), the host B replies to host A at t_b(k). Also, as soon as the response packet is received at the host A at t_a(k+1), the first request is sent to the host B at t_a(k+1). It is repeated during a given period of times.

In Fig. 1 (b), host B is only true clock. Because the interval during a jitter

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measurement is just two RTTs and the effect of clock skew is significantly small, true offsets denoted by $Ofs_a(k)$ and $Ofs_a(k+1)$ are $Ofs_a = Ofs_a(k) = Ofs_a(k+1)$ [5]. By this result, we can define and express k-th RTTs denoted by $R_a(k)$ and $R_b(k)$, k-th true one-way delays denoted by $D_a(k)$ and $D_b(k)$, and k-th jitters denoted by $J_a(k)$ and $J_b(k)$ for each host A and B as follows.

$$\begin{aligned}
R_a(k) &\equiv D_a(k) + D_b(k) \approx t_a(k+1) - t_a(k), \\
R_b(k) &\equiv D_a(k) + D_b(k+1) = t_b(k+1) - t_b(k), \\
D_a(k) &= [t_a(k+1) - t_b(k)] - Ofs_a(k), \\
D_b(k) &= [t_b(k) - t_a(k)] + Ofs_a(k), \\
J_a(k) &\equiv D_a(k+1) - D_a(k) = R_a(k+1) - R_b(k), \\
J_b(k) &\equiv D_b(k+1) - D_b(k) = R_b(k) - R_a(k)(, for\ integer\ k \geq 0). \qquad (1)
\end{aligned}$$

At this point we can know that the jitters can be given using its own and peer's RTTs without a priori clock synchronization [4, 5].

3 Proposed theorem

In Fig. 1 (a), at first, assuming $J_a(k) \neq 0$ and $J_b(k) \neq 0$, a ratio of jitters $J_a(k)/J_b(k)$ can be defined and transformed as Eq. (2).

$$\begin{aligned}
\frac{J_a(k)}{J_b(k)} &\equiv \frac{D_a(k+1) - D_a(k)}{D_b(k+1) - D_b(k)} = \frac{R_a(k+1) - R_b(k)}{R_b(k) - R_a(k)} \\
&= \frac{D_a(k+1)}{D_b(k+1)} \times \left(\frac{1 - \frac{D_a(k)}{D_a(k+1)}}{1 - \frac{D_b(k)}{D_b(k+1)}} \right) = \frac{D_a(k)}{D_b(k)} \times \left(\frac{\frac{D_a(k+1)}{D_a(k)} - 1}{\frac{D_b(k+1)}{D_b(k)} - 1} \right) \qquad (2)
\end{aligned}$$

The ratio is not only defined by the "unknown and true" one-way delays, but also can be expressed by the measured RTTs. Furthermore, assuming that two terms in the parentheses of Eq. (2) are equal to 1, we can conclude that the ratio of one-way delays are equal to the ratio of one-way jitters expressed by the measured RTTs without the clock synchronization as Eq. (3).

$$\begin{aligned}
&\frac{J_a(k)}{J_b(k)} = \frac{D_a(k)}{D_b(k)} = \frac{D_a(k+1)}{D_b(k+1)} = \frac{R_a(k+1) - R_b(k)}{R_b(k) - R_a(k)}, \\
&when \left(\frac{1 - \frac{D_a(k)}{D_a(k+1)}}{1 - \frac{D_b(k)}{D_b(k+1)}} \right) = \left(\frac{\frac{D_a(k+1)}{D_a(k)} - 1}{\frac{D_b(k+1)}{D_b(k)} - 1} \right) = 1. \qquad (3)
\end{aligned}$$

Furthermore, $D_b(k)$, $D_b(k+1)$, $D_a(k)$ and $D_a(k+1)$ can be given by the measured RTTs. In case of synchronized host A and B, we can replace B(k), B(k+1), A(k) and A(k+1) with $D_b(k)$, $D_b(k+1)$, $D_a(k)$ and $D_a(k+1)$ respectively in Eq. (4).

In next section, it is shown how true conditions of Eq. (3) can be practically measured and detected after preliminary case studies of unsynchronized host A and B based on the study of this synchronized case.

4 Estimation of one-way delay and clock offset

4.1 Unsynchronized case study

In Fig. 1 (b), host A and B are not synchronized with each other. Assuming that B(k), A(k), B(k+1) and A(k+1) given by the measured RTTs are equal

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to $t_b(k)$-$t_a(k)$, $t_a(k+1)$-$t_b(k)$, $t_b(k+1)$-$t_a(k+1)$ and $t_a(k+2)$-$t_b(k+1)$ respectively as Eq. (4), the true offset $Ofs_a(k)$ is given as Eq. (5).

$$\begin{aligned} B(k) &= \frac{R_b(k) - R_a(k)}{R_a(k+1) - R_a(k)} R_a(k) = t_b(k) - t_a(k) > 0, \\ A(k) &= \frac{R_a(k+1) - R_b(k)}{R_a(k+1) - R_a(k)} R_a(k) = t_a(k+1) - t_b(k) > 0, \\ B(k+1) &= \frac{R_b(k) - R_a(k)}{R_a(k+1) - R_a(k)} R_a(k+1) = t_b(k+1) - t_a(k+1) > 0, \\ A(k+1) &= \frac{R_a(k+1) - R_b(k)}{R_a(k+1) - R_a(k)} R_a(k+1) = t_a(k+2) - t_b(k+1) > 0. \end{aligned} \tag{4}$$

$$\begin{aligned} Ofs_a(k) &= B(k) - D_b(k) = D_a(k) - A(k) \\ &= B(k+1) - D_b(k+1) = D_a(k+1) - A(k). \end{aligned} \tag{5}$$

And to detect the case of Eq. (4) means that Eq. (3) is true within an error range in case of unsynchronized host A and B as below.

According to Eq. (5), for $Ofs_a(k) > 0$, each of the true measurement times denoted by $t_{a.true}(k)$ and $t_{a.true}(k+1)$ (, note that $t_b(k)$ is true time itself) should be located in each ranges of B(k) and B(k+1), so $Ofs_a(k)$ is bound to smaller one of B(k) and B(k+1), that is $0 \leq Ofs_a(k) \leq \min[B(k), B(k+1)]$. And for $Ofs_a(k) < 0$, $|Ofs_a(k)|$ is bound to smaller one of A(k) and A(k+1), that is $0 \leq |Ofs_a(k)| \leq \min[A(k), A(k+1)]$, vice versa. Furthermore, to minimize an error of the estimated offset denoted by $Ofs_{a.estim}(k)$, it is selected to be half the size of the bounds as Eq. (6).

$$Ofs_{a.estim}(k) = \begin{cases} \min[B(k), B(k+1)]/2, for\ Ofs_a(k) > 0, \\ -\min[A(k), A(k+1)]/2, for\ Ofs_a(k) < 0. \end{cases} \tag{6}$$

Thus the error range of $Ofs_{a.estim}(k)$ denoted by $E_{Ofs}(k) = |Ofs_a(k) - Ofs_{a.estim}(k)|$ is expressed as Eq. (7).

$$\begin{aligned} 0 \leq E_{Ofs}(k) &\leq \begin{cases} \min[B(k), B(k+1)]/2, for\ Ofs_a(k) > 0, \\ \min[A(k), A(k+1)]/2, for\ Ofs_a(k) < 0. \end{cases} \\ &\leq \min[R(k), R(k+1)]/4. \end{aligned} \tag{7}$$

Although $Ofs_{a.estim}(k)$ can be given as Eq. (6), we cannot know which $Ofs_a(k)$ is $Ofs_a(k) > 0$ or $Ofs_a(k) < 0$. However, we can intend to initialize $Ofs_a(i)$ (, for i is an index of the initial offset) so as to be $Ofs_a(k) > 0$ or $Ofs_a(k) < 0$. Furthermore, assuming that the delay asymmetry does not become inversed to the previous state, $E_{Ofs}(k)$ is bound to min[R(k),R(k+1)]/4, because the intentional initial offset $|Ofs_a(i)|$ of min{min[A(i), A(i+1)], min[B(i), B(i+1)]}/2 ensures that $|Ofs_{a.estim}(k)|$ is bound to min[B(k), A(k), B(k+1), A(k+1)]/2. This result means that our estimation error is mathematically twice better than to simply use RTT/2.

The estimated one-way delays denoted by $D_{a.estim}(k)$, $D_{a.estim}(k+1)$, $D_{b.estim}(k)$ and $D_{b.estim}(k+1)$ can be expressed by substituting $Ofs_{a.estim}(k)$ for $Ofs_a(k)$ in Eq. (5).

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4.2 Detection scheme

Practically, it couldn't be expected how often the cases of Eq. (4) are exactly measured in a valid error range(, that is Eq. (3) is true within an error range), since both sides of them are real numbers. That's why we need some criteria.

Before we define specific parameters, three conditions can be identified from Eq. (4) as follows:

1) It should be possible to measure two successive RTTs considering start of the measurement, packet time out and out-of-order packet.

2) $R_a(k)$ and $R_b(k)$ should monotonically increase or decrease, $\{R_a(k) < R_b(k) < R_a(k{+}1)\}$ or $\{R_a(k) > R_b(k) > R_a(k{+}1)\}$.

3) The measured times of $t_a(k)$ and $t_b(k)$ should monotonically increase, $\{t_a(k) < t_b(k) < t_a(k{+}1)\}$ and $\{t_a(k{+}1) < t_b(k{+}1) < t_a(k{+}2)\}$.

According to the above three conditions, we can define a parameter called "measurability" denoted by α, which is a ratio of the measured counts that are satisfied with the three conditions with respect to the total counts of the ping-pong requests.

$$\alpha \equiv \frac{measured\ counts}{total\ ping\ counts} \tag{8}$$

Although the measurability α is a practical criterion which can show how often the cases of Eq. (4) are measured in a valid error range(, that is Eq. (3) is true within the error range of Eq. (7)), we cannot know how the measured values are accurate. Therefore it is necessary to define another criterion to determine accuracy of the measured values, which is called "accuracy factor" denoted by vector $\mathbf{\Delta(k)}$=[δ_0(k), δ_1(k), δ_2(k), δ_3(k)] given as Eq. (9).

$$\begin{aligned}
&\delta_0(k) \equiv B(k)-(t_b(k)-t_a(k)),\ \ \delta_2(k) \equiv B(k{+}1)-(t_b(k{+}1)-t_a(k{+}1)),\\
&\delta_1(k) \equiv A(k)-(t_a(k{+}1)-t_b(k)),\ \ \delta_3(k) \equiv A(k{+}1)-(t_a(k{+}2)-t_b(k{+}1)),\\
&|\Delta(k)| = \sqrt{\delta_0(k)^2+\delta_1(k)^2+\delta_2(k)^2+\delta_3(k)^2}.
\end{aligned} \tag{9}$$

The more δ_0(k), δ_1(k), δ_2(k) and δ_3(k) become close to 0, the more we can get the results close to the exact case of Eq. (4). Thus we can determine more ideally-estimated offset $Ofs_{a.estim}$(m) using Eq. (6) in case of the smallest $|\mathbf{\Delta(m)}|$ of all the measured $|\mathbf{\Delta(k)}|$s.

5 Simulation results and discussion

In this section, we evaluate our proposed scheme by using OMNet++ simulation tool [6]. A simulation network topology is comprised of four hosts s1 to s4, and two routers r1 and r2 as shown in Fig. 2 (a). Host s3 is a standard time server and host s4 is a sink of FTP application. And host s1 is a time client to request timestamps to the time server s3, and host s2 is a source of the FTP application. Hosts and routers are interconnected with PPP(Point-to-Point Protocol) data link protocol over 1.5 Mbps physical links.

The simulation results of the measurability α under the various network traffic conditions are shown in Table I. Drop-tail and RED [7] of PPP queue

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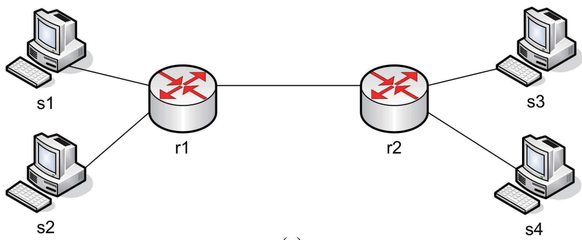
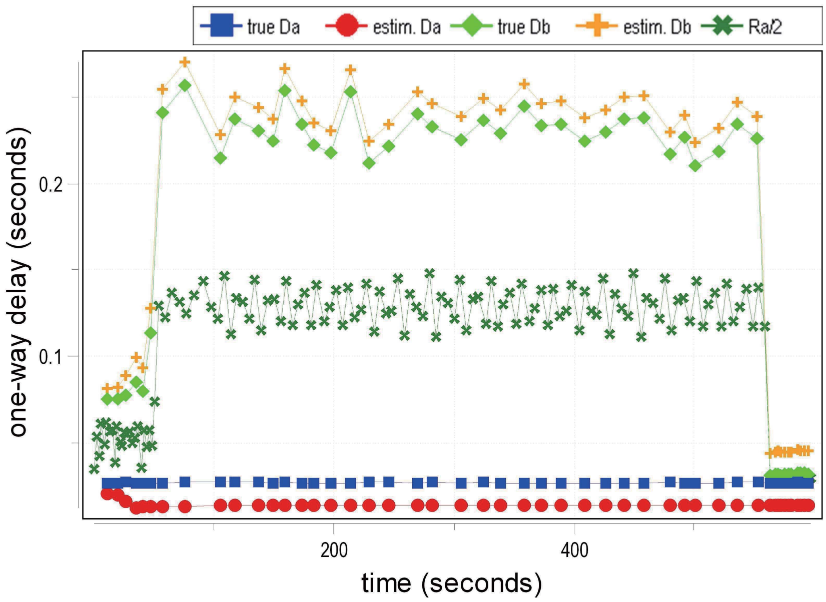
Table I. Measurability α (Total ping counts = 3000)

PPP queue algorithm	Sim. time(s)	Max. queue (packets)	Drop counts	Measured counts	Measurability α(%)
Drop-tail	826.530	10	191	828	27.6
	803.985	30	55	896	29.9
	802.843	50	1	959	32.0
RED	846.278	10	162	809	27.0
	804.842	30	50	879	29.3
	803.385	50	8	960	32.0



(a)



(b)

Fig. 2. (a) Simulation topology. (b) True D_a, D_b vs. estimated D_a, D_b vs. RTT/2.

algorithm in Table I are congestion control algorithms used in PPP receive buffer with the maximum size of 10 to 50 packets. We can know that the less the packets are dropped, the higher the measurability α is. Even though the packets are drastically dropped, the measurability does not be degraded so much. As the measurability α are more than 27%, we can conclude that we have chances to measure and estimate one-way delays or clock offsets for about a third of all of the ping-pong packets under the three conditions of measurability α. The second condition of them can be normally satisfied in case of RTT fluctuations due to network congestions [7].

Fig. 2 (b) shows the window-averaged results (with window size = 20) of our proposal compared with true one-way delays and a half of RTTs under

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the conditions of the last row in Table I. We don't need to compare our proposal with [2] and [5], because their upper limit of the estimation error is not even mathematically smaller than RTT/2. The estimated one-way delays labeled "estim. D_a and estim. D_b" are very closely tracking the true one-way delays labeled "true D_a and true D_b" unlike a half of RTT labeled "$R_a/2$". And we can see that the number of dots of estim. D_a, estim. D_b, true D_a and true D_b are less than the number of dots of $R_a/2$ according to the measurability α.

Finally, our proposal also has the following characteristics:

- It does not assume time synchronization between peer hosts.
- It can track the variations of one-way delays in real time.
- It preferably works well under the network congestions.
- It estimates the delay just using a unit of two successive RTTs, so there are no effects of the cumulative errors according to continuing the measurement.

6 Conclusion

We presented a theorem, methods and simulation results of estimating one-way delays and clock offsets. Our proposal also showed that our estimation error is mathematically smaller than RTT/4. And the simulation results were shown to be practical.

However, we need further studies to determine an optimally-estimated offset and the effects of ping-pong measurement packets.

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