Scheme to Measure Relative Clock Skew of Two Internet Hosts Based on End-Link Capacity

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In this letter, we propose a scheme to measure the relative clock skew between two network nodes. The scheme is based on measuring the intra-packet gaps of probes sent between the two network nodes. We evaluate the proposed scheme through simulation under a heavy cross-traffic load scenario. The obtained results show that the scheme measures the clock skew with high accuracy despite the presence of cross traffic.

Introduction: Existing schemes to measure relative clock skew between two end nodes (i.e., src and dst) of an Internet path are based on sending multiple probing packets and estimating the linear change (i.e., increment or decrement) of the measured one way delay (OWD) [1] over the path [2, 3, 4]. The basic and common principle of these schemes is that the linear change of the measured OWD over time is attributed to the relative clock skew between the end nodes [2]. The measurement of OWD requires heavy statistical analysis, linear programming, and convex-hull optimization on the measured delay samples in order to reduce the affect of cross traffic over the path to measure clock skew [2, 3, 4]. However, the accuracy of these schemes degrades under heavy cross-traffic loads [3, 5]. Therefore, a scheme with immunity to the effect of cross traffic is needed for accurate clock-skew measurement.

In this letter, we propose a scheme to measure the relative clock skew between two network nodes. The scheme is based on sending pairs of probing packets, called compound probes, between the end nodes. Each node measures the intra-packet gap using their own clocks. Intra-packet gaps allow us to selectively use measurements unaffected by cross traffic.

Proposed scheme: The proposed scheme sends compound probes between src and dst, and compares the measured transmission times of a given packet size using the clocks of the end nodes, as shown in Fig. 1. Fig 2 shows the relationship of the measured transmission times and the relative clock skew. To be able to measure the transmission time of a packet, we use compound probes, which is shown in Fig. 3.

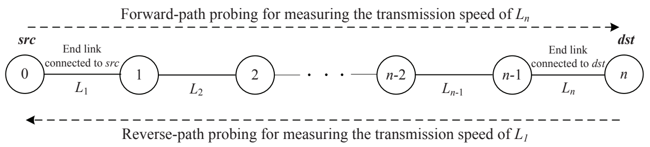

Fig. 1 *An multiple-hop end-to-end path between src and dst consisting of n links*

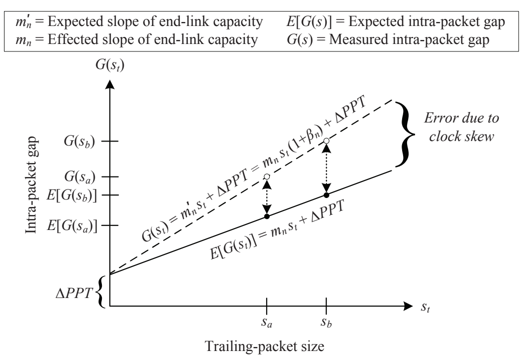

Fig. 2 *Effect of positive clock skew at $node_n$ in the estimation of the end-link capacity L_n using compound probes consisting of two different P_t sizes*

The compound probe consists of a large heading packet P_h followed by a small trailing packet P_t. The intra-packet gap of the compound probe (i.e., the elapsed time between the last bits of P_h and P_t) at the end

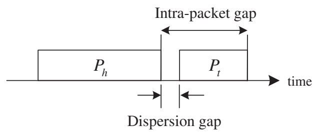

Fig. 3 *A compound probe with a heading packet (P_h) and a trailing packet (P_t)*

node is determined by the capacity of the wired links over a multiple-hop path when the two packets are transmitted back-to-back and without any dispersion (i.e., no separation between the last and the first bits of P_h and P_t, respectively) in between [6].

In the proposed clock-skew measurement, the compound probe must arrive at the remote end node (i.e., the destination) of an end-to-end path with a zero-dispersion gap. Under this condition, the measurement of the transmission time of P_t on the remote end link (i.e., the link connected to the remote end node) indicates the transmission speed of the end link. If s_t is the size of P_t, the relationship between the measured intra-packet gap $G(s_t)$ and the clock skew β_n (relative to a true clock), where $\beta_n \in \mathbb{R}$, of the remote end node, or node n, of a path is:

$$G(s_t) = \frac{s_t}{L_n}(1 + \beta_n) + \Delta PPT \qquad (1)$$

where L_n is the capacity of the end link and ΔPPT is the difference of the packet processing time [1] of the packet pair in the compound probe at node n (i.e., the difference between the time the destination takes to time stamp P_h and P_t at the application layer).

Dispersion in the compound probe depends on the packet-size ratio between P_h and P_t (i.e., $\alpha = \frac{s_h}{s_t}$, where s_h is the size of P_h) and the link-capacity ratio at each node along the path. In Fig. 1, consider that the link capacities of the forward path (src to dst) are L_1, L_2, ..., L_n and the link-capacity ratios are $lr_i = \frac{L_{i+1}}{L_i}$, where $i = \{1, 2, ..., n-1\}$. The required condition to obtain a zero-dispersion gap in a compound probe at node n is:

$$(\frac{s_h}{L_n} - \frac{s_h}{\alpha L_{n-1}}) + (\frac{s_h}{L_{n-1}} - \frac{s_h}{\alpha L_{n-2}}) + ... + (\frac{s_h}{L_{z+1}} - \frac{s_h}{\alpha L_z}) = 0 \qquad (2)$$

In (2), L_z is the capacity of a link such that $lr_z = \frac{L_{z+1}}{L_z}$ is the link-capacity ratio of the node located after the narrow link (i.e., the smallest link capacity) of the forward path, that is also the closest link to the remote end node (i.e., node n) with the largest link-capacity ratio.

From (2), the maximum size of P_t, $s_t(max)$, that ensures a zero-dispersion gap, is determined by:

$$s_t(max) = s_h \frac{\sum_{j=z+1}^{n} \frac{1}{L_j}}{\sum_{j=z}^{n-1} \frac{1}{L_j}} \qquad (3)$$

If L_n is the narrow link of the path, $s_t(max)$ is:

$$s_t(max) = \frac{s_h}{L_n} \times L_{n-1} \qquad (4)$$

For clock-skew measurement at src, the required conditions for a zero-dispersion gap at node 0 and a $s_t(max)$ value over the reverse path (dst to src) are similar to those over the forward path, defined by (2)–(4), as the link capacities L_n, L_{n-1}, ..., L_1 are considered, where L_1 is the remote end link and the link ratios are $lr_i = \frac{L_{i-1}}{L_i}$, where $i = \{n, n-1, ..., 2\}$.

Fig. 4 shows the steps to measure relative clock skew between src and dst over the end-to-end path based on end-link capacity measurements. Here, src and dst send compound probes using two different s_t sizes without any dispersion gap over the forward and reverse paths, respectively. The sizes of s_t in Steps 2 and 7 are calculated using the condition defined by (3) or (4) over the respective paths. Upon receiving the compound probes, the end-link capacities are estimated and these values are compared to the expected values to determine the clock skews of src, β_{src}, and dst, β_{dst}.

In the proposed scheme, the intra-packet gap of a compound probe may experience both decompression, due to cross traffic, and compression, due to Interrupt Coalescence (IC) at the destination [7]. Therefore, if X is a sample set of the measured intra-packet gaps, we apply the following iterative algorithm to determine the smallest intra-packet gap, which is not affected by the above phenomena:

Clock-skew measurement algorithm
1 : Set s_h = Path MTU between src and dst
2 : Set $s_t = s_b$, where $s_b \leq s_t(max)$ over the forward path (src to dst)
3 : Send compound probes with s_h and s_t from src to dst
4 : Get the smallest intra-packet gap $G_{min}(s_b)$
5 : Set $s_t = s_a$, where $s_a < s_b$
6 : Send compound probes with s_h and s_t from src to dst
7 : Get the smallest intra-packet gap $G_{min}(s_a)$
8 : Estimate the slope of the remote end link L_n, $m'_n = \frac{G_{min}(s_b) - G_{min}(s_a)}{s_b - s_a}$
9 : Determine the expected intra-packet gap for s_b on L_n, $E[G(s_b)] = \frac{s_b}{L_n}$
10 : Estimate the clock skew of dst, $\beta_{dst} = \frac{(m'_n \times s_b) - E[G(s_b)]}{E[G(s_b)]}$
11 : Repeat Steps 2 – 7 over the reverse path (dst to src), where $s_t = s_y$ and s_x, respectively, to send compound probes from dst to src for determining $G_{min}(s_y)$ and $G_{min}(s_x)$
12 : Estimate the slope of the remote end link L_1, $m'_1 = \frac{G_{min}(s_y) - G_{min}(s_x)}{s_y - s_x}$
13 : Determine the expected intra-packet gap for s_y on L_1, $E[G(s_y)] = \frac{s_y}{L_1}$
14 : Estimate the clock skew of src, $\beta_{src} = \frac{(m'_1 \times s_y) - E[G(s_y)]}{E[G(s_y)]}$
15 : Calculate the relative clock skew of dst with respect to src, $\beta = \beta_{dst} - \beta_{src}$

Fig. 4 *Proposed scheme for clock-skew measurement over an end-to-end path*

1. Calculate the mean $\bar{x}(j)$ and the standard deviation $\sigma(j)$ of X, where j is the iteration number such that $j \geq 1$.
2. If one of the following conditions is satisfied, stop. Else, go to Step 3.
   a. $\sigma(j) = 0$, for $j \geq 1$.
   b. $\sigma(j) => \sigma(j-1)$, for $j \geq 2$.
3. Discard all data elements in X greater than $\bar{x}(j)$ and go back to Step 1.

The mean value $\bar{x}(1)$ or $\bar{x}(j-1)$ is the smallest intra-packet gap in X if the algorithm terminates after one or j iterations, when $j > 1$, respectively.

Evaluation: We evaluated the proposed scheme through ns-2 simulation [8] using the path shown in Fig. 1, where $n = 4$. According to Table 1, we tested two different relative clock skews, 50 and 250 parts-per-million, between src and dst. We consider two end-link transmission speeds where considered, 100 and 1000 Mb/s, and two bidirectional cross-traffic loads, 75% and 80% on the second ($L_2 = 10$ Mb/s) and third ($L_3 = 155$ Mb/s) links, respectively, of the path were considered. We used $s_h = 1500$ bytes, and $s_t = 75$ and 100 bytes (on both forward and reverse paths) to adopt two large packet-size ratios (i.e., $\frac{1500\ bytes}{75\ bytes} = 20$ and $\frac{1500\ bytes}{100\ bytes} = 15$, respectively) in the compound probes to ensure a zero-dispersion gap in each path direction. We used 50 compound-probes for both s_t sizes to measure clock skew at each end node, and $\Delta PPT = 1$ μs at src and dst. Table 2 shows the obtained simulation results. In this table, the clock skew measured by the proposed scheme (see $src\ skew$ and $dst\ skew$ columns) are the same as those expected at src and dst (see $Clock\ skews$ column of Table 1). These results show that the scheme achieves both high accuracy and immunity to heavy cross-traffic load.

Table 1: Simulation setup

Clock skews (ppm) β_{src}, β_{dst}	Relative clock skew (ppm) β	End link (Mb/s) L_1	L_4	Packet processing time (μs) ΔPPT	Forward path s_t (bytes) s_a	s_b	Reverse path s_t (bytes) s_x	s_y
25, 75	50	100	100	1	75	100	75	100
25, 75	50	100	1000	1	75	100	75	100
250, 500	250	100	100	1	75	100	75	100
250, 500	250	100	1000	1	75	100	75	100

Table 2: Simulation results of the proposed scheme

Forward path measurement				Reverse path measurement			
Smallest gaps (μs) $G_{min}(s_a), G_{min}(s_b)$	Slope m'_n	Expected gap (μs) $E[G(s_b)]$	dst skew (ppm) β_{dst}	Smallest gaps (μs) $G_{min}(s_x), G_{min}(s_y)$	Slope m'_1	Expected gap (μs) $E[G(s_y)]$	src skew (ppm) β_{src}
7.00045, 9.0006	0.080006	8	75	7.00015, 9.0002	0.080002	8	25
1.600045, 1.80006	0.0080006	0.8	75	7.00015, 9.0002	0.080002	8	25
7.003, 9.004	0.08004	8	500	7.0015, 9.002	0.08002	8	250
1.6003, 1.8004	0.008004	0.8	500	7.0015, 9.002	0.08002	8	250

Conclusions: We proposed a scheme to measure the relative clock skew, which is based on sending compound probes over an end-to-end path in forward- and reverse-path directions. The scheme relies on receiving compound probes at the end nodes with a zero-dispersion gap to measure the transmission speeds of the end links through intra-packet gap measurement. The comparison of the measured and the expected transmission speeds is used to estimate the clock skew. The scheme can estimate the relative clock skew accurately using a small number of probing packets because the compound probe and the data-analysis algorithm are designed to detect the intra-packet gaps affected by cross traffic on a path. We evaluated the proposed scheme through simulation and the obtained value shows that it can estimate the relative clock skew accurately even under a heavy (e.g., 80%) cross-traffic load.

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