Improvement of Jitter, Wander, and Time Synchronization Performance in 802.1AS Wired Transport using Propagation Time Averaging

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Outline

- Background
- Description of Propagation Time Averaging

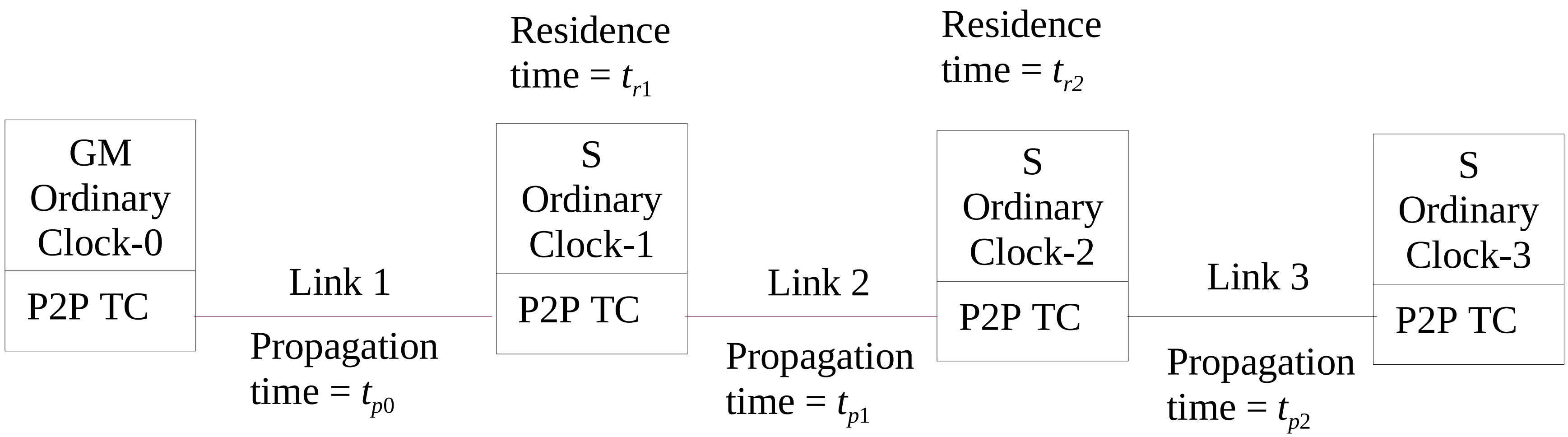
Background - 1

- In [1], when synchronization is transported over a wired (802.3) network, phase offset at an endpoint (slave) is computed as

$$offset\_from\_master = T2 - T1 - R1 - D1$$

- where
  - $T2$ = time stamp for arrival of message at slave
  - $T1$ = time stamp for sending of message from master
  - $R1$ = accumulated residence time at Peer-to-Peer (P2P) Transparent Clocks (TCs) between master and endpoint
  - $D1$ = accumulated propagation time over all links between master and endpoint

Background - 2



$$offset\_from\_master\_at\_Ordinary\_Clock-3 = T2 - T1 - R1 - D1$$

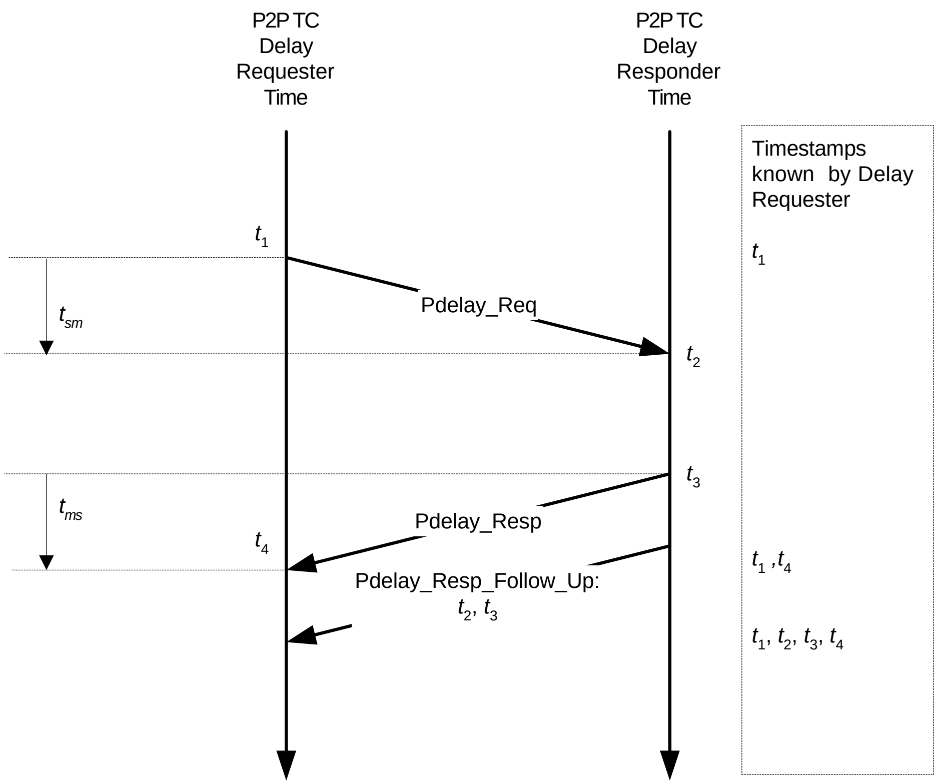
$T2$ = time stamp for arrival of message at Ordinary Clock-3
$T1$ = time stamp for sending of message from GM (Ordinary Clock-1)

$$D1 = t_{p0} + t_{p1} + t_{p2}$$

$$R1 = t_{r1} + t_{r2}$$

Background - 3

❑ Measurement of propagation time using Pdelay messages



$$t_{sm} = t_2 - t_1$$

$$t_{ms} = t_4 - t_3$$

$$T_{mean-prop} = \frac{t_{sm} + t_{ms}}{2} = \frac{t_2 - t_1 + t_4 - t_3}{2}$$

Prop Time Meas Error due to Phase Meas Granul

- Propagation time is expected to be measured less frequently than phase offset, because propagation time on a wired link is expected to be relatively static
- For example
  - Sync and Follow_Up messages will be sent on the order of every 10 ms
  - Propagation time could be measured every 100 ms, or every 1 s
- Phase measurement granularity can be on the order of 40 ns
  - This corresponds to a 25 MHz clock, which is the requirement for Ethernet and the expected requirement for 802.1AS
- Since mean propagation delay involves the sum/difference of four time stamp values, divided by 2, the propagation time measurement error component due to phase measurement granularity can be as large as 80 ns per link
  - This means that for a wired connection of seven hops, the propagation time error component due to phase measurement granularity can have standard deviation as large as $(\sqrt{7})(80\text{ ns}) = 212\text{ ns}$ and peak-to-peak as large as $7(80\text{ ns}) = 560\text{ ns}$
- While this component of propagation time measurement error will be filtered by any endpoint PLLs, the required PLL bandwidths to achieve a given level of performance may need to be narrower due to less frequent propagation time measurement

Propagation Time Measurement Averaging - 1

- One simple approach to reducing the component of propagation time measurement error due to phase measurement granularity is to average the successive propagation time measurements
- This scheme assumes that the propagation time is relatively stable, as is the case for wired Ethernet (802.3)
- The measured propagation time on a single link tends to fluctuate between two values
  - The greatest integer multiple of the clock granularity that is less than the propagation time, and
  - The least integer multiple of the clock granularity that is greater than the propagation time
- Since the successive propagation time measurements are independent, the time average of the error due to phase measurement granularity will converge to zero
- Several approaches may be used for averaging
  - Method 1: Use sliding window of length M
  - Method 2: Use general linear digital filter (actually, generalization of Method 1)

Propagation Time Measurement Averaging - 2

❑Method 1: Sliding window of length M

- In this method, the current and most recent $M - 1$ values of measured propagation time are averaged

$$D_k = D_{k-1} + \frac{d_k - d_{k-M}}{M}$$

$$H(z) = \frac{1}{M} \cdot \frac{1 - z^{-M}}{1 - z^{-1}}$$

- Where
  - $d_k = k^{\text{th}}$ measured value of the propagation time (i.e., at time step k), which is in error due to phase measurement granularity
  - $D_k = k^{\text{th}}$ estimate of the actual propagation time (i.e., at time step k)
  - $M =$ number of propagation time measurement samples in average (i.e., size of sliding window)
  - $H(z) =$ transfer function for difference equation for D_k

Propagation Time Measurement Averaging - 3

- M should be chosen to be large compared with the number of samples over which the d_k vary
  - For 40 ns phase measurement granularity and 7 links, potential accumulated error due to this effect has standard deviation of 212 ns (see slide 6)
  - For window of length M, standard deviation of error due to this effect is reduced to (212 ns)/$\sqrt{M}$
    - 26.5 ns for $M = 64$
    - 13.3 ns for $M = 256$
    - 6.63 ns for $M = 1024$
- Note that while the reduction in phase error is significant (185.5 – 205.4 ns in the examples above), large *M* may be required to reduce the phase error due to this component to sufficiently small value (e.g., < 1 ns)

Propagation Time Measurement Averaging - 4

❑Method 2: general linear digital filter

- In this method, the sequence of measured propagation time values are input to a linear digital filter, to produce an estimate of the actual propagation time

$$D_k = a_1 D_{k-1} + a_2 D_{k-2} + \cdots + a_n D_{k-n} + b_0 d_k + b_1 d_{k-1} + \cdots + b_m d_{k-m}$$

$$H(z) = \frac{b_0 + b_1 z^{-1} + \cdots + b_m z^{-m}}{1 - a_1 z^{-1} - a_2 z^{-2} - \cdots - a_n z^{-n}}$$

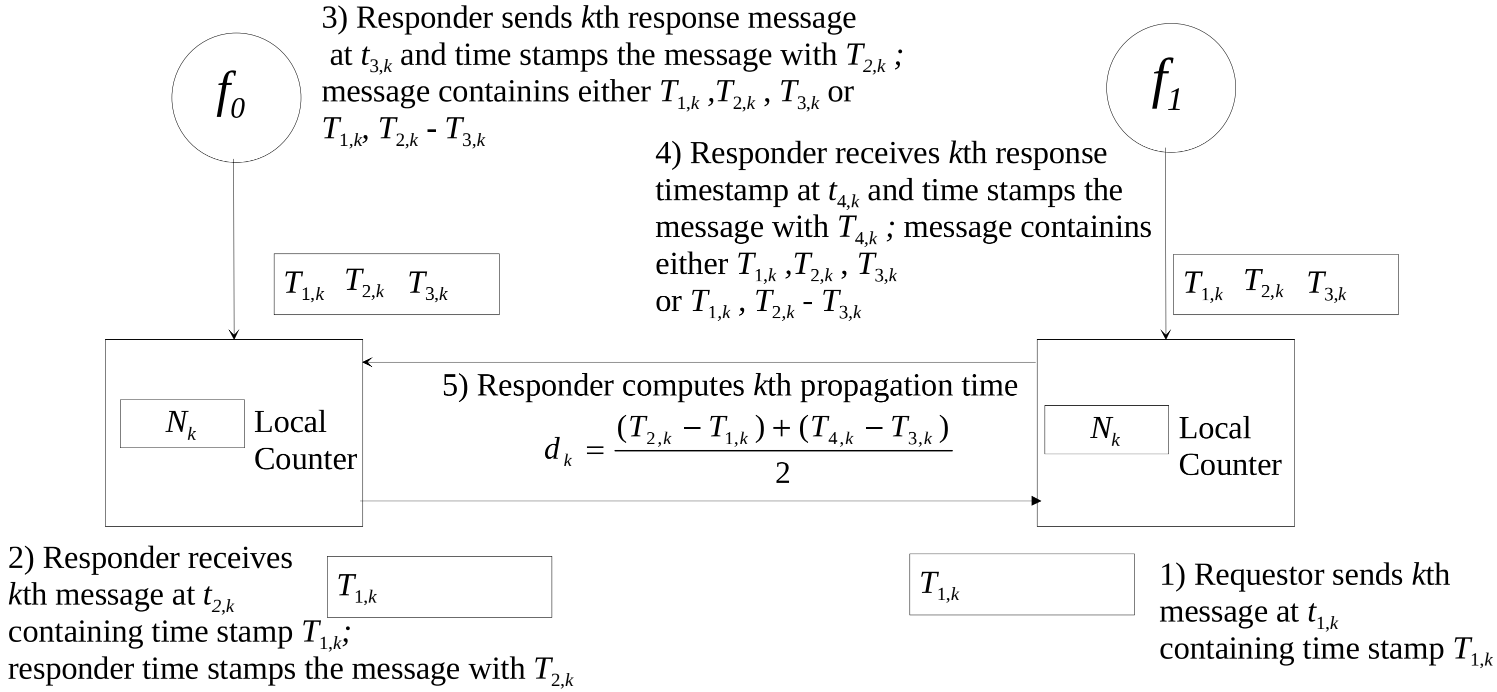
- Where
  - $d_k = k^{\text{th}}$ measured value of the propagation time (i.e., at time step k), which is in error due to phase measurement granularity
  - $D_k = k^{\text{th}}$ estimate of the actual propagation time (i.e., at time step k)
  - The a_j and b_j are filter coefficients, and $H(z)$ is the filter transfer function
  - In order that the filter output converge to the actual propagation time, the filter coefficients must satisfy

$$a_1 + a_2 + \cdots + a_n + b_0 + b_1 + \cdots + b_m = 1$$

Propagation Time Measurement Averaging - 5

- The bandwidth of the digital filter should be small compared to the discrete frequency of variation of the d_k
- Which of the two methods is more convenient will depend on implementation requirements
  - Method 1 requires saving M values of measured propagation time, whereas method 2 requires saving n values of D_k and m values of d_k
    - Equivalent performance can be obtained with method 2 compared to method 1, but with fewer saved values of measured and average propagation time (i.e., $m < M$, $n < M$, $m+n < M$)
    - E.g., in method 2 can choose small m and n but small equivalent bandwidth
    - Method 1 may require large M
  - Good performance with method 2 may require filter coefficients that are not conveniently represented as binary integers
    - In contrast, method 1 is easily implemented with M a power of 2

Propagation Time Measurement Averaging - 6



6) Responder computes current averaged propagation time D_k in terms of current and past propagation times d_k and possibly past averaged propagagtion times D_{k-n} , n = 1, 2, 3, ..., M

Method 1 (sliding window of size M average):

$$D_k = D_{k-1} + \frac{d_k - d_{k-M}}{M}$$

$$H(z) = \frac{1}{M} \cdot \frac{1 - z^{-M}}{1 - z^{-1}}$$

$H(z)$ is the transfer function

Method 2 (general linear digital filter average):

$$D_k = a_1 D_{k-1} + a_2 D_{k-2} + \cdots + a_n D_{k-n} + b_0 d_k + b_1 d_{k-1} + \cdots + b_m d_{k-m}$$

$$H(z) = \frac{b_0 + b_1 z^{-1} + \cdots + b_m z^{-m}}{1 - a_1 z^{-1} - a_2 z^{-2} - \cdots - a_n z^{-n}}$$

The a_i and b_i are filter coefficients; $H(z)$ is the filter transfer function

References

1. IEEE P802.1AS/D0.6, *Timing and synchronization for time sensitive applications in bridged local area networks*, January 3, 2007 (available at http://www.ieee802.org/1/files/private/as-drafts/d0/802-1AS-d0-6.pdf)