Modelling Packet Delay in Ethernet and IP Networks

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Introduction

- Is it possible to transfer time and frequency over packet switched networks with accuracies commonly required by telecom applications and equipment?
- If yes, under what conditions?
- Take as an example the ‘Precise Time Protocol’ (IEEE 1588)
- Use simulations to study packet propagation properties and predict performance
- Study the influence of traffic load
- Study the influence of protocol support in switching/routing nodes (e.g. Transparent Clocks)
**Definition: Packet Delay $\delta_{AB}(k)$**

Consider two interfaces A and B traversed by a given packet flow.
Definition: Packet Delay Asymmetry $A(k)$

Consider two interfaces A and B traversed by bi-directional paired packet flows, where the k-th packet pair experiences the delay $\delta_{AB}(k)$ and $\delta_{BA}(k)$:

$$A(k) = \delta_{AB}(k) - \delta_{BA}(k)$$
PTP IEEE 1588: TWTT

Master (M)

\[ t_M \]

Slave (S)

\[ t_S = t_M + \theta \]

\[ T_1 \quad \text{SYNC} \quad T_2 \]

\[ T_1 \quad \text{FOLLOW\_UP} (T_1) \quad T_1 \]

\[ T_3 \quad \text{DELAY\_REQ} \quad T_3 \]

\[ T_4 \quad \text{DELAY\_RESP} (T_4) \quad T_4 \]

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Time-critical message

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Timestamp transfer message
PTP IEEE 1588: Time-stamping

Lower Layers of Protocol Stack

PTP Protocol Entity

Local Clock

Transport Layer

Network Layer

Data Layer

Physical Layer

Precise Time Stamp Generator

Physical Network Medium
PTP IEEE 1588: Transparent Clocks
**End-to-end Transparent Clock**

\[
\bar{\theta} = \frac{(T_2 - T_1) - (T_4 - T_3)}{2} = \theta + \frac{\delta_{M\rightarrow S} - \delta_{S\rightarrow M}}{2} = \theta - \frac{A}{2}
\]

PTP with End-to-end Transparent Clocks:

\[
\bar{\delta}_{M\rightarrow S} = \sum \delta_{\text{NODE}, M\rightarrow S}
\]

\[
\bar{A} = \sum \bar{\delta}_{\text{NODE}, M\rightarrow S} - \sum \bar{\delta}_{\text{NODE}, S\rightarrow M}
\]

\[
\bar{\theta} = \frac{(T_4 - T_3) - (T_2 - T_1)}{2} - \frac{\bar{A}}{2}
\]
Simulation: network structure

M = PTP Master
S = PTP Slave
T = Traffic Source & Sink

= Switch or Router
Traffic sources

- Each source bloc shown in the diagram represents 5 independent smaller sources with the same stochastic properties.
- Packet interarrival times process: « walker held by an elastic leash »
- Packet sizes:

<table>
<thead>
<tr>
<th>Packet size [octet]</th>
<th>1518</th>
<th>506</th>
<th>126</th>
</tr>
</thead>
<tbody>
<tr>
<td>Probability</td>
<td>0.6</td>
<td>0.3</td>
<td>0.1</td>
</tr>
</tbody>
</table>
Simulation: node structure
Simulation scenarios

<table>
<thead>
<tr>
<th>Run no.</th>
<th>Traffic load $\lambda$</th>
<th>$N_N$</th>
<th>$X = \text{non-PTP-capable node}$</th>
<th>$O = \text{PTP-capable node}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.16</td>
<td>2</td>
<td>- O - X - X - O - O - O - O -</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>0.16</td>
<td>4</td>
<td>- O - X - X - X - X - O -</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>0.43</td>
<td>6</td>
<td>- X - X - X - X - X - X -</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>0.43</td>
<td>2</td>
<td>- O - X - X - O - O - O -</td>
<td></td>
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<tr>
<td>5</td>
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<td>6</td>
<td>- X - X - X - X - X - X -</td>
<td></td>
</tr>
</tbody>
</table>

Traffic load $\lambda = \text{(avg. data rate / link capacity)}$ on a longitudinal link

$N_N = \text{number on non-PTP-capable nodes}$
Simulation parameters and output

Simulation parameters:
- Link capacity $C = 100$ Mbit/s
- Input queues = 150,000 octets
- Output queues = 150,000 octets
- TWTT interrogation rate = 100 s$^{-1}$ (SYNC & DELAY_REQ)
- Sampling period $T_S = 10$ µs
- Simulation length = 30,000 s
- ($=>$ 400 mio. samples on 68 sources and nodes!)

Main simulation output:
- Residual Packet Delay $\delta_{R,M\rightarrow S} = \delta_{M\rightarrow S} - \bar{\delta}_{M\rightarrow S}$
- Residual Packet Delay Asymmetry $A_R = \bar{A} - A$
Simulator State Display
MinTDEV of residual delay $\delta_R$:

$$\text{MinTDEV}(\tau) = \sqrt{\frac{1}{8} \left( [\delta_{R,+min}(i+2n) - 2\delta_{R,min}(i+n) + \delta_{R,min}(i)]^2 \right)}$$

where

$\tau = n\tau_0$, $\tau_0 =$ sampling period

$\delta_{R,min}(i) = \min \{\delta_R(j)\}$ for $\forall j : i \leq j \leq i+n$

'Min'TDEV of residual asymmetry $A_R$:

$$'\text{Min}'\text{TDEV}(\tau) = \sqrt{\frac{1}{8} \left( [A_{R,+min}(i+2n) - 2A_{R,min}(i+n) + A_{R,min}(i)]^2 \right)}$$

where

$\tau = n\tau_0$, $\tau_0 =$ sampling period

$A_{R,min}(i) = \min \{\delta_{R,M\rightarrow S}(j) - \min \{\delta_{R,S\rightarrow M}(j)\}\}$ for $\forall j : i \leq j \leq i+n$
Histogram of 2 x Residual Delay

\[ \lambda = 0.16 \]

\[ \lambda = 0.43 \]
TDEV of 2 x Residual Delay

\[ \tau \text{ [s]} \]

\[ \text{TDEV (} \tau \text{) [µs]} \]

\[ \lambda = 0.16 \]

\[ \lambda = 0.43 \]

\[ N_N = 6 \]

\[ N_N = 4 \]

\[ N_N = 2 \]
MinTDEV of Residual Delay

MinTDEV ($\tau$) [µs]

$\lambda = 0.16$

$N_N = 6$
$N_N = 4$
$N_N = 2$

MinTDEV ($\tau$) [µs]

$\lambda = 0.43$

$N_N = 6$
$N_N = 4$
$N_N = 2$
Histogram of Residual Asymmetry

\[ \frac{N_i}{N} \]

- 800 - 400 0 400 800 \( A_R [\mu s] \)

\[ \lambda = 0.16 \]

\[ \lambda = 0.43 \]

- 800 - 400 0 400 800 \( A_R [\mu s] \)
TDEV of Residual Asymmetry

λ = 0.16

λ = 0.43

TDEV (τ) [µs]

N_N = 6
N_N = 4
N_N = 2

τ [s]
‘Min’TDEV\(^{(1)}\) of Residual Asymmetry

\[ \lambda = 0.16 \]

\[ \lambda = 0.43 \]

1: In the MinTDEV definition, replace \( x_{\min} \) by \( \min[\delta_{M\rightarrow S}] - \min[\delta_{S\rightarrow M}] \)
Filtering Residual Delay

\[ \tau_c = 300 \, \text{s} \]
\[ f_c = 1 \, \text{mHz} \]
\[ \text{TDEV}(2 \cdot \delta R), \lambda = 0.43, N_N = 6 \]

\[ \tau_c = 40 \, \text{s} \]
\[ f_c = 7.5 \, \text{mHz} \]
\[ \text{TDEV}(2 \cdot \delta R), \lambda = 0.43, N_N = 6 \]

2 x Network Limit for PDH distribution output, ITU-T Rec. G.823
Filtering Residual Asymmetry

2 x Network Limit for PDH distribution output, ITU-T Rec. G.823

\[ \tau_c = 300 \text{ s} \]
\[ f_c = 1 \text{ mHz} \]

Min. TDEV(A_R), \( \lambda = 0.43 \), \( N_N = 6 \)

2 x Network Limit for PDH distribution output, ITU-T Rec. G.823

\[ \tau_c = 4 \text{ s} \]
\[ f_c = 75 \text{ mHz} \]
Conclusions

- With PTP IEEE 1588 telecom performance level is achievable over moderate size networks
- If traffic load is controlled, performance objectives are attained even in PTP networks without PTP-capable nodes
- High traffic loads deteriorate performance in PTP networks without PTP-capable nodes
- PTP suitable for the distribution of time and frequency in network types such as Metro Area Networks, base-station backhaul networks, access aggregation networks, etc.
Thank you