Testing Packet Time and Frequency

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Introduction

• Frequency Transport
  • One-way: forward and reverse packet streams can be used separately
  • Asymmetry is irrelevant
  • Stable frequency needed
  • PRC (primary reference clock) needed
  • GNSS/GPS antenna cable compensation/calibration not needed
  • GSM frequency backhaul (50 ppb) is example technology

• Time Transport
  • Two-way: forward and reverse packet streams used together
  • Asymmetry is critical
  • Stable time and frequency needed
  • PRTC (primary reference time clock) or ePRTC (enhanced PRTC) needed
  • GNSS/GPS antenna cable compensation/calibration needed
  • LTE-TDD time/phase (1.5 µsec) is an example technology
Testing Frequency “Physical” vs. “Packet”

● **“TIE” (Single Point Measurement)** Measurements are made at a single point – a single piece of equipment in a single location – a phase detector with reference – is needed

![Image depicting single point measurement](image)

0 µs 1.001 µs 1.997 µs 3.005 µs

● **“PDV” (Dual Point Measurement)** Measurements are constructed from packets time-stamped at two points – in general two pieces of equipment, each with a reference, at two different locations – are needed

<table>
<thead>
<tr>
<th>Timestamp A</th>
<th>Timestamp B</th>
</tr>
</thead>
<tbody>
<tr>
<td>F 1233166476.991204496</td>
<td>1233166476.991389744</td>
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<tr>
<td>R 1233166476.980521740</td>
<td>1233166476.980352932</td>
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<tr>
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<td>1233166477.022639568</td>
</tr>
<tr>
<td>R 1233166477.011771820</td>
<td>1233166477.011602932</td>
</tr>
</tbody>
</table>
Testing Time “Physical” vs. “Packet”

- **“1 PPS” (Single Point Measurement)** Measurements are made at a single point – a single piece of equipment in a single location – a phase detector with reference – is needed.

  - 0 s 1.000 000 001 s 1.999 999 997 s 3.000 000 005 s

- **“Packet” (Dual Point Measurement)** Measurements are constructed from packets time-stamped at two points – in general two pieces of equipment, each with a reference, at two different locations – are needed.

<table>
<thead>
<tr>
<th>Timestamp A</th>
<th>Timestamp B</th>
</tr>
</thead>
<tbody>
<tr>
<td>F 1286231440.883338640</td>
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<tr>
<td>R 1286231441.506929352</td>
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<tr>
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</tr>
<tr>
<td>R 1286231442.506929352</td>
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<tr>
<td>F 1286231442.883338640</td>
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</tr>
<tr>
<td>R 1286231443.506929352</td>
<td>1286231443.506929516</td>
</tr>
</tbody>
</table>

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Grandmaster Test PPS and Packet Probe

Physical 1 PPS signal measurement and packet signal tested with probe match
“TIE” Analysis vs. “PDV” Analysis

“TIE” Analysis  (G.810)
- Phase (TIE)
- Frequency accuracy
- Dynamic frequency
- MTIE
- TDEV

“PDV” Analysis  (G.8260)
- Phase (PDV)
- Histogram/PDF*, CDF**, statistics
- Dynamic statistics
- MATIE/MAFE
- TDEV/minTDEV/bandTDEV

* PDF = probability density function
** CDF = cumulative distribution function

The importance of raw TIE/PDV:
- Basis for frequency/statistical/MTIE/TDEV analysis
- Timeline (degraded performance during times of high traffic?)
- Measurement verification (jumps? offsets?)
Stability Metrics

• Traditional Clock Metrics
  • ADEV, TDEV, MTIE
  • Traditionally applied to oscillators, synchronization interfaces
  • Also applied to lab packet equipment measurements

• Frequency Transport Packet Metrics
  • minTDEV, MAFE, MATIE
  • Applied to one-way packet delay data
  • FPP/FPR/FPC (floor packet percentage/rate/count)

• Time Transport Packet Metrics
  • pktselected2wayTE
  • Applied to two-way packet delay data
  • Assesses link asymmetry
Stability Metrics for PDV

- **Packet Selection Processes**
  1) **Pre-processed**: packet selection step prior to calculation. Example: \( TDEV(PDV_{\text{min}}) \) where \( PDV_{\text{min}} \) is a new sequence based on minimum searches on the original PDV sequence
  2) **Integrated**: packet selection integrated into calculation. Example: \( \text{min}TDEV \) (PDV)

- **Packet Selection Methods**
  - **Minimum**: \( x_{\text{min}}(i) = \min \{ x_j \} \text{ for } i \leq j \leq i + n - 1 \)
  - **Percentile**: \( x'_{\text{pct} \_\text{mean}}(i) = \frac{1}{m} \sum_{j=0}^{b} x'_{j+i} \)
  - **Band**: \( x'_{\text{band} \_\text{mean}}(i) = \frac{1}{m} \sum_{j=a}^{b} x'_{j+i} \)
  - **Cluster**: \( x(n \tau_0) = \frac{\sum_{i=0}^{(K-1)} w(nK+i) \cdot \phi(n,i)}{\sum_{i=0}^{(K-1)} \phi(n,i)} \)
    \( \phi(n,i) = \begin{cases} 1 \text{ for } |w(nK+i) - \alpha(n)| < \delta \\ 0 \text{ otherwise} \end{cases} \)
Packet Selection Windows

• Windows
  • *Non-overlapping windows* (next window starts at prior window stop)
  • *Skip-overlapping windows* (windows overlap but starting points skip over N samples)
  • *Overlapping windows* (windows slide sample by sample)

• Packet Selection Approaches
  • Select X% fastest packets (e.g. 2%)
  • Select N fastest packets (e.g. 10 fastest packets in a window)
  • Select all packets faster than Y (e.g. all packets faster than 150 μs)
G.8260 Appendix I Metrics

- **Pre-processed packet selection**
  - Entire PDV population
  - Stability metric with packet selection
  - Estimated achievable performance

- **Integrated packet selection**
  - Entire PDV population
  - Stability metric with packet selection
  - Estimated achievable performance
  - G.8260(10)_FI.4

- **Metrics including pre-filtering**
  - Packet Selection
  - Bandwidth Filtering
  - Stability Metric
  - Filtered-Packet Time Error Sequence
  - Estimated achievable performance

- **PDV metrics studying minimum floor delay packet population**

FPC, FPR, FPP: Floor Packet Count/Rate/Percent

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Packet Delay Distribution

Minumum: 1.904297 usec  Mean:  96.71927 usec
Maximum: 275.2441 usec  Standard Deviation: 97.34 usec
Peak to Peak: 273.3 usec  Population: 28561  Percentage: 100.%

50 pct: 37.65 us;  90 pct: 245.5 us;  95 pct: 261.9 us;  99 pct: 272.3 us;  99.9 pct: 274.5 us
Time Accuracy and Stability Requirements

**Packet Network Limits**

- **Deployment Case 1**
  - Time Reference: e.g. GNSS Engine
  - MTIE (PRTC-A) is G.811 with 100 ns maximum
  - TDEV (PRTC-A) is G.811 exactly

- **Deployment Case 2**
  - Time Reference: e.g. GNSS Engine

**Time Accuracy**

- Time Error:
  - <=100 ns (PRTC-A)
  - <=40 ns (PRTC-B)
  - <=30 ns (ePRTC)

**Time Stability**

- MTIE (PRTC-A) is G.811 with 100 ns maximum
- TDEV (PRTC-A) is G.811 exactly

A: Time Error: <=100 ns
C: Time Error: <=1.1 µs
Time Transport: Two-Way Metrics

Packet Time Transport Metrics

**MeanPathDelay:**

\[ r(n) = \left( \frac{1}{2} \right) \cdot [R(n) + F(n)] \]

**TwowayTimeError:**

\[ \eta_2(n) = \left( \frac{1}{2} \right) \cdot [R(n) - F(n)] \]

**pktSelectedMeanPathDelay:**

\[ r'(n') = \left( \frac{1}{2} \right) \cdot [R'(n') + F'(n')] \]

**pktSelectedTwowayTimeError:**

\[ \eta'_2(n') = \left( \frac{1}{2} \right) \cdot [R'(n') - F'(n')] \]

**Ideal F/R: floor**

("lucky" packets: fastest)

**Ideal 2way TE: zero**

(no asymmetry)

**Weighted Average:**

\[ w(n) = [a \cdot F(n) + (1-a) \cdot R(n)] \]

where \( 0 \leq a \leq 1 \)

\[ \text{where } 0 \leq a \leq 1 \]
Time Transport: Two-Way Packet Delay

Forward Packet Delay Sequence:
- #Start: 2019/03/06 17:15:30
- 0.0000, 1.47E-6
- 0.1000, 1.54E-6
- 0.2000, 1.23E-6
- 0.3000, 1.40E-6
- 0.4000, 1.47E-6
- 0.5000, 1.51E-6

Reverse Packet Delay Sequence:
- #Start: 2019/03/06 17:15:30
- 0.0000, 1.11E-6
- 0.1000, 1.09E-6
- 0.2000, 1.30E-6
- 0.3000, 1.13E-6
- 0.4000, 1.22E-6
- 0.5000, 1.05E-6

Minimum Search Sequence:
- Constructing \( f' \) and \( r' \) from \( f \) and \( r \) with a 3-sample time window

Two-Way Data Set:

<table>
<thead>
<tr>
<th>Time(s)</th>
<th>( f(\mu s) )</th>
<th>( r(\mu s) )</th>
<th>( f'(\mu s) )</th>
<th>( r'(\mu s) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0</td>
<td>1.47</td>
<td>1.11</td>
<td></td>
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</tr>
<tr>
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<td>1.09</td>
<td>1.23</td>
<td>1.09</td>
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<td>1.12</td>
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<td></td>
</tr>
<tr>
<td>0.3</td>
<td>1.40</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>0.4</td>
<td>1.47</td>
<td>1.22</td>
<td>1.40</td>
<td>1.05</td>
</tr>
<tr>
<td>0.5</td>
<td>1.51</td>
<td>1.05</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**min2wayTE**

\[
\eta_2'(n') = \left(\frac{1}{2}\right) \cdot [R'(n') - F'(n')]
\]

<table>
<thead>
<tr>
<th>Time(s)</th>
<th>min2wayTE(\mu s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1</td>
<td>-0.07</td>
</tr>
<tr>
<td>0.4</td>
<td>-0.18</td>
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Time Transport: Two-Way Metrics

2wayTE

pktSelected2wayTE

Both 2wayTE and pktSelected2wayTE plots with minimum set to 0. Mean value from unadjusted data.

Selection window = 200s
Selection percentage = 0.25%
Peak-to-peak pktSelected2wayTE = 663 ns
(G.8271.2 APTS limit: <1100 ns)
Two-Way Time Error ↔ Network Asymmetry

Asymmetry in Wireless Backhaul

(Ethernet wireless backhaul asymmetry and IEEE 1588 client 1PPS under these asymmetrical network conditions)
Network Asymmetry

150 km fiber PTP over OTN transport

(2wayTE is 19.1 µsec which represents the 38.2 µsec difference between forward and reverse one-way latencies)
Summary

• PDV frequency measurements only require a stable reference

• PDV time measurements require common time scale reference at both ends of the network being studied (GNSS at both ends is a way to do this)

• For frequency transport, asymmetry doesn’t matter, and one, the other, or both packet flows can be used

• Asymmetry is everywhere, asymmetry is invisible to the IEEE 1588 protocol, thus asymmetry has a direct bearing on the ability to transport time precisely

• The “two-way time error” calculation is a direct measure of asymmetry

• There are two ways to assess time transport: (1) measuring a 1 PPS reference at the node being studied and (2) measuring a packet signal at the node being studied

• Packet metrics for time transport must use both forward and reverse streams together rather than separately as is the case for frequency transport

• Packet metrics for time transport can make use of much of the methodology used for packet frequency transport metrics
Thank you

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