Timing Measurements and Metrics for Frequency, Time, and Packet Signals

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Presentation Outline

• Introduction
  – TIE vs. PDV
  – Frequency vs. Time
  – Network vs. Equipment Measurements
  – Phase Detector and Packet Probe

• Metrics: Synchronization and Packet Analysis
  – TIE and PDV based metrics (G.810 and G.8260)
  – Packet selection processes and methods
  – Frequency transport PDV metrics
  – Time transport PDV metrics

• Measurement Case Studies
  – Networks
    • Time/frequency transport
  – Equipment
    • GM, BC, PRTC

• Conclusions
“TIE” vs. “PDV”

• “TIE” vs “PDV”
  – Traditional TDM synchronization measurements: signal edges are timestamped producing a sequence of samples
  – Packet timing measurements: packet departure/arrival times are sampled and packet delay sequences are formed
  – Both require (1) PRC/GPS; (2) Precision HW timestamping; (3) PC + SW

• Measurement equipment:
  – TIE: Counters, TIA’s, Test-sets, BITS, SSU, GPS receivers
  – PDV: IEEE 1588 probes, NTP probes, network probes

• TIE measurements are still important in a packet world:
  – Needed for the characterization of packet servo slaves such as IEEE 1588 slave devices
  – There are still oscillators and synchronization interfaces to characterize
  – “TIE” measurement/analysis background important to the understanding of “PDV” measurement/analysis
  – Many of the tools can be applied to either “TIE” or “PDV” data such as TDEV or spectral analysis
  – But there are new tools and new approaches to be applied to “PDV” with some of the traditional “TIE” tools less effective for “PDV” analysis
TIE Measurements: Network vs. Equipment

Network TIE

Equipment TIE
PDV Measurements: Network vs. Equipment

Network PDV

Equipment PDV
Packet Probe

Network PDV Measurement

PTP/NTP Equipment Characterization

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Network PDV Measurement

Packet Equipment Characterization
Frequency signal “TIE” vs. “PDV”

- **“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

- **“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>
</tr>
<tr>
<td>F 1233166477.006829496</td>
<td>1233166477.007014512</td>
</tr>
<tr>
<td>R 1233166476.996147084</td>
<td>1233166476.995977932</td>
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<td>F 1233166477.022454496</td>
<td>1233166477.022639568</td>
</tr>
<tr>
<td>R 1233166477.011771820</td>
<td>1233166477.011602932</td>
</tr>
</tbody>
</table>
Time signal “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

• “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>
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<tr>
<td>F 1286231440.883338640</td>
<td>1286231440.883338796</td>
</tr>
<tr>
<td>R 1286231441.506929352</td>
<td>1286231441.506929500</td>
</tr>
<tr>
<td>F 1286231441.883338640</td>
<td>1286231441.883338796</td>
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<tr>
<td>R 1286231442.506929352</td>
<td>1286231442.506929500</td>
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<tr>
<td>F 1286231442.883338640</td>
<td>1286231442.883338796</td>
</tr>
<tr>
<td>R 1286231443.506929352</td>
<td>1286231443.506929516</td>
</tr>
</tbody>
</table>

0 s 1.000 000 001 s 1.999 999 997 s 3.000 000 005 s
“PDV” Measurement Setup Options

Passive Probe
1. Hub or Ethernet Tap
2. IEEE 1588 Slave
3. Collection at Both Nodes

Active Probe
1. No Hub or Ethernet Tap Needed
2. No IEEE 1588 Slave Needed
3. Collection at Probe Node Only

“PDV”
- Ideal setup - two packet timestampers with GPS reference so absolute latency can be measured as well as PDV over small to large areas
- Alternative setup (lab) – frequency (or GPS) locked single shelf with two packet timestampers
- Alternative setup (field) – frequency locked packet timestampers – PDV but not latency can be measured
Either PTP or NTP packets can be used for probing.

- In some circumstances, one or the other might be more suitable.
- For example, NTP is useful for probing over the public internet because of NAT (network address translation) challenges.
In most packet network measurement setups, both “TIE” and “PDV” are measured at the same time.
## “TIE” Analysis vs. “PDV” Analysis

<table>
<thead>
<tr>
<th><strong>“TIE” Analysis</strong> (G.810)</th>
<th><strong>“PDV” Analysis</strong> (G.8260)</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Phase (TIE)</td>
<td>• Phase (PDV)</td>
</tr>
<tr>
<td>• Frequency accuracy</td>
<td>• Histogram/PDF*, CDF**, statistics</td>
</tr>
<tr>
<td>• Dynamic frequency</td>
<td>• Dynamic statistics</td>
</tr>
<tr>
<td>• MTIE</td>
<td>• MATIE/MAFE</td>
</tr>
<tr>
<td>• TDEV</td>
<td>• TDEV/minTDEV/bandTDEV</td>
</tr>
<tr>
<td></td>
<td>• Two-way metrics: minTDISP etc.</td>
</tr>
</tbody>
</table>

### 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?)

*PDF = probability density function*

**CDF = cumulative distribution function**
Stability Metrics

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

• Frequency Transport Packet Metrics
  – minTDEV, MAFE, MATIE
  – Applied to one-way packet delay data

• Time Transport Packet Metrics
  – minOffset, minTDISP
  – Applied to two-way packet delay data
  – Assesses link asymmetry

Packet Networks
Analysis from Phase: Frequency

Frequency Accuracy

$$\omega = \frac{d\phi}{dt}$$

slope/linear: frequency offset
curvature/quadratic: frequency drift

Point-by-point

Segmented LSF

Sliding Window Averaging
MTIE is a peak detector
MTIE detects frequency offset

TDEV is a highly averaged “rms” type of calculation
TDEV shows white, flicker, random walk noise processes
TDEV does not show frequency offset

MTIE and TDEV analysis allows comparison to ATIS, Telcordia, ETSI, & ITU-T requirements
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: \( \min TDEV(PDV) \)

- **Packet Selection Methods**
  - Minimum: \( x_{\text{min}}(i) = \min \{x_j\} \text{ for } i \leq j \leq i+n-1 \)
  - Percentile: \( x'_{\text{perc_mean}}(i) = \frac{1}{m} \sum_{j=0}^{b} x'_{j+i} \)
  - Band: \( x'_{\text{band_mean}}(i) = \frac{1}{m} \sum_{j=a}^{b} x'_{j+i} \)
  - 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** (e.g. selecting fastest packets)
  - 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 150μs)
G.8260 Appendix I Metrics

Figure I.3 – Pre-processed packet selection

Figure I.4 – Integrated packet selection

Metrics including pre-filtering

PDV metrics studying minimum floor delay packet population

FPC, FPR, FPP: Floor Packet Count/Rate/Percentage
Packet Delay Sequence

Packet Delay Sequence

R, 00162; 1223305830.478035356; 1223305830.474701511
F, 00167; 1223305830.488078908; 1223305830.49052012
R, 00163; 1223305830.492882604; 1223305830.489969511
F, 00168; 1223305830.503473436; 1223305830.505803244
R, 00164; 1223305830.508647148; 1223305830.505821031
F, 00169; 1223305830.519029300; 1223305830.521302172
R, 00165; 1223305830.524413852; 1223305830.521446071
F, 00170; 1223305830.534542972; 1223305830.536801164
R, 00166; 1223305830.540181132; 1223305830.537115991
F, 00171; 1223305830.550229692; 1223305830.552551628

Packet Timestamps

Forward

#Start: 2009/10/06 15:10:30
0.0000, 2.473E-3
0.0155, 2.330E-3
0.0312, 2.273E-3
0.0467, 2.258E-3
0.0623, 2.322E-3

Reverse

#Start: 2009/10/06 15:10:30
0.0000, 3.334E-3
0.0153, 2.913E-3
0.0311, 2.826E-3
0.0467, 2.968E-3
0.0624, 3.065E-3
Packet Delay Distribution

Minimum: 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: 100.0%

50pct: 37.65 us; 90pct: 245.5 us; 95pct: 261.9 us; 99pct: 272.3 us; 99.9pct: 274.5 us
Tracked Packet Delay Statistics

Raw packet delay appears relatively static over time

Mean vs. time shows cyclical ramping more clearly

Standard deviation vs. time shows a quick ramp up to a flat peak
minTDEV, bandTDEV, MATIE, MAFE

TDEV

\[ \sigma_x(\tau) = TDEV(\tau) = \sqrt{\frac{1}{n} \left( \frac{1}{n} \sum_{i=1}^{n} x_{i+2n} - 2 \frac{1}{n} \sum_{i=1}^{n} x_{i+n} + \frac{1}{n} \sum_{i=1}^{n} x_i \right)^2} \]

minTDEV

\[ \sigma_{x_{\text{min}}}(\tau) = \min TDEV(\tau) = \sqrt{\frac{1}{n} \left( x_{\min}(i+2n) - 2x_{\min}(i+n) + x_{\min}(i) \right)^2} \quad x_{\min}(i) = \min \lfloor x_j \rfloor \text{ for } i \leq j \leq i+n-1 \]

bandTDEV

\[ \sigma_{x_{\text{band}}}(\tau) = \text{bandTDEV}(\tau) = \sqrt{\frac{1}{n} \left( x'_{\text{band\_mean}}(i+2n) - 2x'_{\text{band\_mean}}(i+n) + x'_{\text{band\_mean}}(i) \right)^2} \quad x'_{\text{band\_mean}}(i) = \frac{1}{b} \sum_{j=i}^{i+b} x_{j+i} \]

1. TDEV is bandTDEV(0.0 to 1.0)
2. minTDEV is bandTDEV(0.0 to 0.0)
3. percentileTDEV is bandTDEV(0.0 to B) with B between 0.0 and 1.0

MATIE

\[ \text{MATIE}(n\tau_0) \approx \max_{1 \leq k \leq N-2n+1} \frac{1}{n} \left| \sum_{i=k}^{n+k-1} (x_{i+n} - x_i) \right| , \quad n = 1, 2, \ldots, \text{integer part } (N/2) \]

MAFE

\[ \text{MAFE}(n\tau_0) = \frac{\text{MATIE}(n\tau_0)}{n\tau_0} \]

\[ \text{minMAFE}(n\tau_0) \approx \frac{\max_{1 \leq k \leq N-2n+1} \left| \sum_{i=k}^{n+k-1} (x_{\min}(i+n) - x_{\min}(i)) \right|}{n\tau_0} \quad \text{where } n = 1, 2, \ldots, \text{integer part } (N/2) \text{ and where } x_{\min}(i) = \min \lfloor x_j \rfloor \text{ for } i \leq j \leq i+n-1 \]

References:
Lower levels of noise with the application of a MINIMUM selection algorithm minTDEV at various traffic levels on a switch (0% to 50%) converge.

Symmetricom TimeMonitor Analyzer (file=multilayer_switch_40percentSB60.txt)
minTDEV: No. Avg=1; Fo=10.00 MHz; 2006/09/19; 15:28:30
Packet Time Transport

“PDV” measurement setup for time transport

- Ideal setup - two packet timestampers with GPS reference so absolute latency can be measured as well as PDV over small to large areas
- Alternative setup (lab) – frequency (or GPS) locked single shelf with two packet timestampers

- Alternative setup (field) – frequency locked packet timestampers – PDV but not latency can be measured
## Metrics: Time Transport

### Forward Packet Delay Sequence

- **#Start:** 2010/03/06 17:15:30
- Time(s) | f(µs) | r(µs) | f'(µs) | r'(µs)
---|---|---|---|---
0.0 | 1.47E-6 | 1.11E-6 |
0.1 | 1.54E-6 | 1.09E-6 |
0.2 | 1.23E-6 | 1.12E-6 |
0.3 | 1.40E-6 | 1.13E-6 |
0.4 | 1.47E-6 | 1.22E-6 |
0.5 | 1.51E-6 | 1.05E-6 |

### Reverse Packet Delay Sequence

- **#Start:** 2010/03/06 17:15:30
- Time(s) | f(µs) | r(µs) | f'(µs) | r'(µs)
---|---|---|---|---
0.0 | 1.47E-6 | 1.11E-6 |
0.1 | 1.54E-6 | 1.09E-6 |
0.2 | 1.23E-6 | 1.12E-6 |
0.3 | 1.40E-6 | 1.13E-6 |
0.4 | 1.47E-6 | 1.22E-6 |
0.5 | 1.51E-6 | 1.05E-6 |

### Constructing $f'$ and $r'$ from $f$ and $r$ with a 3-sample time window

Two-way Data Set

Minimum Search Sequence
Packet Time Transport Metrics

**Normalized roundtrip:**

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

**Normalized offset:**

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

**\(\min\)Roundtrip:**

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

**\(\min\)Offset:**

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

**\(\min\)TDISP (minimum time dispersion):** \(\min\)Offset \(\{y\}\) plotted against \(\min\)Roundtrip \(\{x\}\) as a scatter plot

**\(\min\)Offset statistics:** \(\min\)Offset statistic such as mean, standard deviation, or 95 percentile plotted as a function of time window \(\tau\).
minOffset Statistics
(Two-way minimum offset statistics vs. $\tau$)

Two-way MAFE
(MAFE of minOffset)
Asymmetry in Wireless Backhaul

(Ethernet wireless backhaul asymmetry and IEEE 1588 slave 1PPS under these asymmetrical network conditions)
Case Studies: Networks

Packet measurement

Packet data analysis:
1PPB offset predicted

Sync measurement

1588 slave performance:
1 PPB offset measured
Metro Ethernet Network

Forward and reverse packet delay sequences with zooms into the respective floors and minTDISP

National Ethernet Network

Forward PDV floor 4.54 ms
Reverse PDV floor 4.53 ms
Case Studies: Networks

Public Internet w/ Cable Modem Access (NTP probe)

Downstream maintains 8.7 msec minimum
Upstream minimum steps from 4.9 msec to 6.4 msec for 35 minutes

Public Internet w/ ADSL Modem Access (NTP probe)

Downstream typically 9.0 msec minimum
Upstream typically 6.7 msec minimum, steps to 70 msec for 1 hour
Not shown: delays as much as several seconds
Case Studies: Grandmaster Clock

Grandmaster Measurement Setup

- GPS
- GigE
- 1588 Master
- 1588 Probe
- 2.048 MHz
- PDV Measurement Software
- Time Interval Measurement Software
- Cesium Clock
- 1 PPS
Case Studies: Grandmaster Clock

Raw unfiltered probe measurement

Overlay of filtered probe and 1PPS measurement
Case Studies: Grandmaster Clock

Traditional Metrics Applied to Filtered Probe Measurement

MTIE below G.811 PRC mask

TDEV below G.811 PRC mask
Case Studies: Boundary Clocks

Boundary Clock Measurement Setup

1588 Master

Cesium Clock

1588 Slave

Boundary Clock

1588 Probe #1

1588 Probe #2

Time Interval Measurement Software

PDV Measurement Software

Network

gigE

PPS

FE

PDV Measurement Software
Case Studies: Boundary Clocks

Boundary Clock Measurement: 3 Approaches
(1) Packet probe; (2) BC 1PPS; (3) Connected slave 1PPS
Case Studies: Boundary Clocks

Three boundary clocks from three vendors

BC Vendor #1

BC Vendor #2

BC Vendor #3
Case Studies: Boundary Clocks

Loaded 8-node network

Symmetricom TimeMonitor Analyzer
MTIE; F0=1.000 Hz; Fs=498.9 mHz; 2011/04/09; 09:24:40

BC #1: 1.6µs @24h
BC #2: 32µs @24h
BC #3: 102µs @24h
Case Studies: Four GPS Receivers

Measurement Setup

GPS receivers share the same antenna
Case Studies: Four GPS Receivers

Raw GPS vs. cesium 1PPS

GPS measurements with cesium offset removed
Characterizing PRTC Accuracy

• A stable and accurate time reference is required. A cesium clock alone will not suffice.

• Possible candidates for such a reference:
  – National metrology lab reference
  – Carefully calibrated “golden” reference GPS receiver

• We need to understand both the accuracy and the stability characteristics of such a reference.

• We need to consider that both the reference and the PRTC under test may deliver different performance under conditions of constant temperature and varying temperature.
Note: Measurements conducted at constant room temperature.
“Golden” Receiver Stability Performance

Raw results vs. 3 cesium clocks
Cesium 1 (blue): 3.573E-13
Cesium 2 (red): 1.579E-13
Cesium 3 (violet): -5.428E-13

Results with respective cesium offsets removed

Zoom into 12 hour section of 10-day measurement
“Golden” Receiver Stability Performance

Symmetricom TimeMonitor Analyzer
Phase deviation in units of time: Fe=1.000 Hz; Fo=1.0000000 Hz; 2012/02/03; 15:35:09
RefGPS (violet) and GM (gray) measured against cesium

Symmetricom TimeMonitor Analyzer
Phase deviation in units of time: Fe=1.000 Hz; Fo=1.0000000 Hz; 2012/02/03; 15:35:09
4 (green). Phase: Samples: 8311/0; HP 53132A; Avg 74/75/76 5.6 days, 2012/02/03; 15:35:09

“Golden” vs. conventional GPS receiver

Three “Golden” measurements averaged together
"Golden" Receiver Stability Performance

"Golden" receiver MTIE performance

"Golden" receiver TDEV performance
Summary

• Types of measurements
  – Frequency, Time, and Packet Signals
  – “TIE” vs. Packet “PDV”
  – Network vs. Equipment
  – Packet probes: passive vs. active, PTP vs. NTP

• Clock and Packet Analysis
  – TIE analysis methods inform approach to PDV analysis
  – Stability metrics (1) Preprocessed or (2) Integrated packet selection
  – Frequency transport metrics
  – Time transport metrics

• Measurement Case Studies
  – Networks
    • Wireless backhaul: frequency and asymmetry
    • Metro/National Ethernet (PTP probe)
    • ADSL/Cable modem access (NTP probe)
  – Equipment
    • IEEE 1588 GM & BC (measurements on physical signal or packet signal)
    • PRTC: Four GPS receiver comparison (common antenna and common measurement reference)
    • PRTC: “Golden” receiver stability
Thank You

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