Time and Frequency Measurements in Synchronization and Packet Networks

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Presentation Outline

- Introduction
  - Synchronization “TIE” vs. packet “PDV” measurements
  - Measurement equipment overview

- Synchronization Measurements
  - Measuring TIE
  - Analysis from TIE

- Packet Metrics
  - Packet delay distribution
  - Tracked packet delay statistics
  - Frequency transport metrics
  - Time transport metrics

- Case Studies
  - Asymmetry in microwave, SHDSL, wireless backhaul
  - Metro Ethernet network
  - National Ethernet network
“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

Phase measurements (TIE) can be made using:
- Frequency/time interval counters
- Time interval analyzers
- Dedicated test-sets
- BITS/SSU clocks with built-in measurement capability
- GPS receivers with built-in measurement capability

Packet phase measurements (PDV) can be made using:
- IEEE 1588 grandmaster/probes
- NTP servers/probes
- Specialized network probes
“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

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

**Timestamp A**
- F 1233166476.991204496 1233166476.991389744
- R 1233166476.980521740 1233166476.980352932
- F 1233166477.006829496 1233166477.007014512
- R 1233166477.096147084 1233166477.095977932
- F 1233166477.02454496 1233166477.024639568
- R 1233166477.011771820 1233166477.011602932

**Timestamp B**
- F 1233166476.991204496 1233166476.991389744
- R 1233166476.980521740 1233166476.980352932
- F 1233166477.006829496 1233166477.007014512
- R 1233166477.096147084 1233166477.095977932
- F 1233166477.02454496 1233166477.024639568
- R 1233166477.011771820 1233166477.011602932
**“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
“TIE” in a Packet World

Are “TIE” Measurements still important? Yes!

- 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
In most packet network measurement setups, both “TIE” and “PDV” are measured at the same time.
Network Emulator

Symmetricom TimeMonitor Analyzer; Live Network; 2009/03/04; 17:06:25

Symmetricom TimeMonitor Analyzer; Network Emulator; 2009/07/21; 23:33:10

Live Network

Network Emulator
TIE Measurement and Analysis: 3 step process

1. Timestamps

2. Phase

3. Analysis

MTIE, TDEV, Allan Variance, Frequency, PPSD, etc.
The Importance of Phase (TIE)

1. **Analysis**: Frequency/MTIE/TDEV etc. derived from phase

2. **Check**: Verify measurement is properly made
   - Sudden (point-to-point) large movements of phase are suspect. For example, if MTIE fails the mask, it could be a measurement problem. Phase will help to investigate this.
   - Large frequency offset is easily seen: Is the reference OK? Is the equipment set to use the external reference?

3. **Timeline**: The processed measurements don’t show what happened over time. Is the measurement worse during peak traffic times? Is the measurement worse in the middle of the night during maintenance activities?
Analysis from Phase: Jitter & Wander

Signal (no filter)

Jitter (high-pass filter) 1.52 UI peak-to-peak (E1)

Wander (low-pass filter)
Recall the relationship between frequency and phase:

\[ \omega = \frac{d\phi}{dt} \]

Important point: Frequency is the slope in the phase plot.

Frequency offset present

No offset: ideal phase plot (flat)

We can reduce a phase ramp to a single frequency value.
Approaches to Frequency Calculation

- **Point-by-point**
- **Segmented LSF**
- **Sliding Window Averaging**
Frequency Offset and Drift

Original oscillator phase measurement (0.7ppm frequency offset)

Frequency offset removed (quadratic shape shows linear frequency drift of 0.2 ppb/day)

Frequency drift removed (shows residual phase movement)
**Analysis from Phase: MTIE/TDEV**

\[
MTIE(S) = \max_{j=1}^{N-n+1} \left[ \max_{i=j}^{n+j-1} (x_i) - \min_{i=j}^{n+j-1} (x_i) \right]
\]

MTIE is a peak detector
MTIE detects frequency offset

\[
\sigma_x(\tau) = TDEV(\tau) = \sqrt{\frac{1}{6} \left[ \frac{1}{n} \sum_{i=1}^{n} x_{i+2n} - 2 \frac{1}{n} \sum_{i=1}^{n} x_{i+n} + \frac{1}{n} \sum_{i=1}^{n} x_i \right]^2}
\]

TDEV is a highly averaged “rms” type of calculation
TDEV shows white, flicker, random walk noise processes
TDEV does not show frequency offset
For traditional synchronization measurements, the measurement analysis used primarily is:

- Phase (TIE)
- Frequency (fractional frequency offset)
- Frequency accuracy
- MTIE
- TDEV

MTIE and TDEV analysis shows comparison to ANSI, Telcordia/Bellcore, ETSI, & ITU-T requirements

All are derived from phase
Interpretation of Measurement Results ("PDV")

For packet synchronization measurements, some of the measurement analysis used is:

- Phase (PDV)
- Histogram/PDF* & Statistics
- Running Statistics
- MATIE/MAFE
- TDEV/minTDEV/bandTDEV
- Two-way metrics such as minTDISP

minTDEV is under study at the ITU-T Q13/SG15 and has references in the latest G.8261 draft

* PDF = probability density function
Packet Delay Sequence

Packet Delay Sequence

R,00162; 1223305830.478035356; 1223305830.474701511
F,00167; 1223305830.488078908; 1223305830.490552012
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

#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

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
Packet Delay Sequence

When graphing packet delay phase it is often best not to connect the dots.

![Graph showing packet delay phase]

Measurement points connected

Measurement points as discrete dots
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%

Symmetricom TimeMonitor Analyzer
Phase Deviation Histogram: Fs=500.0 mHz; Fo=10.00 MHz; 2006/06/09 01:11:06
Tahiti Phase; Samples: 28561; UUID: 000055010016; Initial phase offset: 12.5420 usec
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.
MATIE/MAFE Packet Metrics

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

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

To define \text{bandTDEV}, it is first necessary to represent the sorted phase data. Let \(x'\) represent this sorted phase sequence from minimum to maximum over the range \(i \leq j \leq i+n-1\). Next it is necessary to represent the indices which are themselves set based on the selection of two percentile levels. Let \(a\) and \(b\) represent indices for the two selected percentile levels. The averaging is then applied to the \(x'\) variable indexed by \(a\) and \(b\). The number of averaged points \(m\) is related to \(a\) and \(b\): \(m=b-a+1\).

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

References: *Definition of Minimum TDEV (\text{minTDEV}), WD 27, ITU-T Q13/15, Geneva, June 2007*
TDEV with Traffic

Symmetricom TimeMonitor Analyzer
TDEV: No. Avg=1, Fc=10.00 MHz. 2006/06/06 21:27:56

TDEV

No load  5%  10%  20%  30%  50%
Lower levels of noise with the application of a MINIMUM selection algorithm TDEV at various traffic levels on a switch (0% to 50%) converge.
Loaded Multilayer Switch: TDEV and minTDEV

Mean: 48.3 μsec / Peak to Peak: 50.9 μsec / Standard Deviation: 9.43 μsec
Two-way Data Set

<table>
<thead>
<tr>
<th>Forward Packet Delay Sequence</th>
<th>Reverse Packet Delay Sequence</th>
</tr>
</thead>
<tbody>
<tr>
<td>#Start: 2009/10/06 15:10:30</td>
<td>#Start: 2009/10/06 15:10:30</td>
</tr>
<tr>
<td>0.0000, 2.473E-3</td>
<td>0.0000, 3.334E-3</td>
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<tr>
<td>0.0623, 2.322E-3</td>
<td>0.0624, 3.065E-3</td>
</tr>
</tbody>
</table>

Two-way Data Set
Minimum Search Sequences

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

<table>
<thead>
<tr>
<th>Time(s)</th>
<th>f(µs)</th>
<th>r(µs)</th>
<th>f'(µs)</th>
<th>r'(µs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0</td>
<td>1.47</td>
<td>1.11</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.1</td>
<td>1.54</td>
<td>1.09</td>
<td>1.23</td>
<td>1.09</td>
</tr>
<tr>
<td>0.2</td>
<td>1.23</td>
<td>1.12</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.3</td>
<td>1.40</td>
<td>1.13</td>
<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>
Packet Time Transport Metrics

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

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

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

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

**\( minTDISP \) (minimum time dispersion):** \( minOffset \) \{y\} plotted against \( minRoundtrip \) \{x\} as a scatter plot

**\( minOffset \) statistics:** \( minOffset \) statistic such as mean, standard deviation, or 95 percentile plotted as a function of time window \( \tau \)
minTDISP
(minOffset vs. minRoundtrip)
Metrics: Time Transport

minOffset Statistics
(Two-way minimum offset statistics vs. $\tau$)
Asymmetry in Microwave Transport
(Ethernet microwave radio packet delay pattern asymmetry)

Symmetricom TimeMonitor Analyzer; uWave Radio Forward PDV; 2009/06/23; 23:53:31

µWave Forward PDV

Symmetricom TimeMonitor Analyzer; uWave Radio Reverse PDV; 2009/06/23; 23:53:31

µWave Reverse PDV

244 µs
226 µs
226 µs
226 µs

2 µs/div
2 µs/div
2 µs/div
2 µs/div

0.0 minutes 30 sec/div 7.5 minutes

7.5 minutes

0.0 minutes
Asymmetry in SHDSL

(SHDSL forward/reverse packet delay asymmetry)
Asymmetry in Wireless Backhaul

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

Symmetricom TimeMonitor Analyzer; Ethernet Wireless Backhaul; 2009/04/28; 11:37:01

Min TDISP

1588 Slave 1 PPS vs. GPS

TDISP 0.5 µs/div

0.0 hours 22.7 hours
Metro Ethernet Network

Forward PDV floor

Reverse PDV floor

Metro Ethernet 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

minTDISP 0.0 days 1.63 days