Packet Network Timing Measurements and Metrics: An Introduction

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Presentation Outline

• Introduction
  – Types of measurements:
    1. Synchronization “TIE”
    2. Packet “PDV”
  – Measurement equipment overview

• Synchronization and Packet Analysis
  – TIE and PDV based metrics
  – Packet selection processes and methods
  – Comments on windowing
  – Frequency transport metrics

• Time Transport Measurements
  – Measurement equipment and setup
  – Time transport metrics

• Network Measurements
  – Lab/production packet network measurements
“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” 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

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<thead>
<tr>
<th>Timestamp A</th>
<th>Timestamp B</th>
</tr>
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<tbody>
<tr>
<td>F 1233166476.991204496</td>
<td>1233166476.991389744</td>
</tr>
<tr>
<td>R 1233166476.980521740</td>
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</tr>
<tr>
<td>R 1233166477.011771820</td>
<td>1233166477.011602932</td>
</tr>
</tbody>
</table>
“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
In most packet network measurement setups, both “TIE” and “PDV” are measured at the same time.

**Network Emulator**

1588 Grandmaster

GPS

1588 Probe

GPS

1588 Slave

GPS

Probe

E1 or T1

PDV Measurement Software

Sync Measurement Software

Network

IP

IP

IP
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.
“TIE” Analysis vs. “PDV” Analysis

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

“PDV” Analysis
- Phase (PDV)
- Histogram/PDF*, CDF**, statistics
- Dynamic statistics
- MATIE/MAFE
- TDEV/minTDEV/bandTDEV
- Two-way metrics: minTDISP etc.

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
Analysis from Phase: Frequency

-8.97 \times 10^{-14}

Frequency Accuracy

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

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

Point-by-point

Segmented LSF

Sliding Window Averaging
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

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: $TDEV(PDV_{min})$ where $PDV_{min}$ 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: $x_{\text{min}}(i) = \min \{x_j\} \text{ for } i <= j <= i+n-1$
  – Percentile: $x'_{\text{pct\_mean}}(i) = \frac{1}{m} \sum_{j=0}^{b} x'_{j+i}$
  – 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)
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

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%

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

minTDEV
\[ \sigma_{x_{\text{min}}}(\tau) = \text{minTDEV}(\tau) = \sqrt{\frac{1}{6} \left( \left[ x_{\min}(i + 2n) - 2 x_{\min}(i + n) + x_{\min}(i) \right]^2 \right)} \quad x_{\min}(i) = \min \left[ x_j \right \text{ for } i \leq j \leq i + n - 1 \]

bandTDEV
\[ \sigma_{x_{\text{band}}}(\tau) = \text{bandTDEV}(\tau) = \sqrt{\frac{1}{6} \left( \left[ x'_{\text{band}_\text{mean}}(i + 2n) - 2 x'_{\text{band}_\text{mean}}(i + n) + x'_{\text{band}_\text{mean}}(i) \right]^2 \right)} \quad x'_{\text{band}_\text{mean}}(i) = \frac{1}{m} \sum_{j=i}^{b} x'_{j+i} \]

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

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

minMAFE
\[ \min \text{MAFE} \left( n \tau_0 \right) \approx \frac{\max_{1 \leq k \leq N-2n+1} \left| \sum_{i=k}^{n+k-1} (x_{\min}(i + n) - x_{\min}(i)) \right|}{n \tau_0} \quad x_{\min}(i) = \min \left[ x_j \right \text{ for } i \leq j \leq i + n - 1 \]

Lower levels of noise with the application of a MINIMUM selection algorithm minTDEV at various traffic levels on a switch (0% to 50%) converge.
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
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: 2010/03/06 17:15:30
0.0000, 1.11E-6
0.1000, 1.09E-6
0.2000, 1.12E-6
0.3000, 1.13E-6
0.4000, 1.22E-6
0.5000, 1.05E-6

Two-way Data Set

Time(s)  f(µs)  r(µs)  f'(µs)  r'(µs)
0.0     1.47   1.11
0.1     1.54   1.09   1.23    1.09
0.2     1.23   1.12
0.3     1.40   1.13
0.4     1.47   1.22   1.40    1.05
0.5     1.51   1.05

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

Minimum Search Sequence
Packet Time Transport Metrics

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

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

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

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

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

\( \text{minOffset statistics} \): minOffset 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)
Case Studies

Asymmetry in Wireless Backhaul
(Ethernet wireless backhaul asymmetry and IEEE 1588 slave
1PPS under these asymmetrical network conditions)
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
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
Summary

• Types of measurements discussed
  1. “TIE” vs. Packet “PDV”
  2. Extra requirements when studying packet time transport

• Types of 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

• Network Measurements
  – Lab/production packet network measurements shown
  – Packet time transport studies
  – NTP probe useful over public internet
Thank You

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