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"

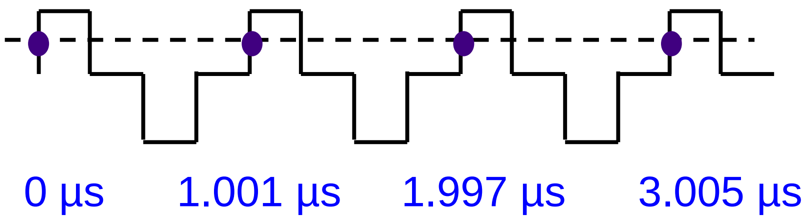
- "TIE" vs "PDV"
  - Traditional TDM synchronization measurements: signal edges are timestamped producing a sequence of samples
  - Packet timing measurements: packet departure/arrival times are sampled and packet delay sequences are formed
  - Both require (1) PRC/GPS; (2) Precision HW timestamping;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

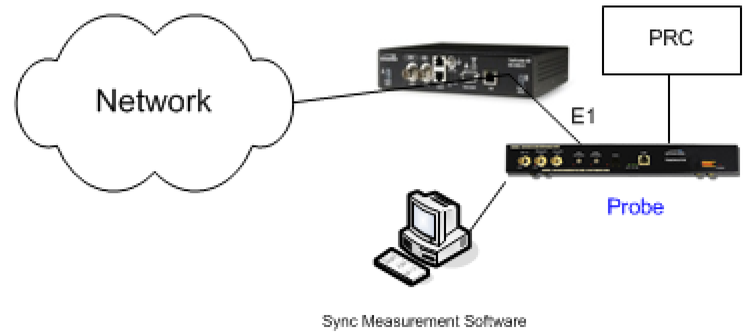
- Measurement equipment:
  - TIE: Counters, TIA's, Test-sets, BITS, SSU, GPS receivers
  - PDV: IEEE 1588 probes, NTP probes, network probes

- 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"

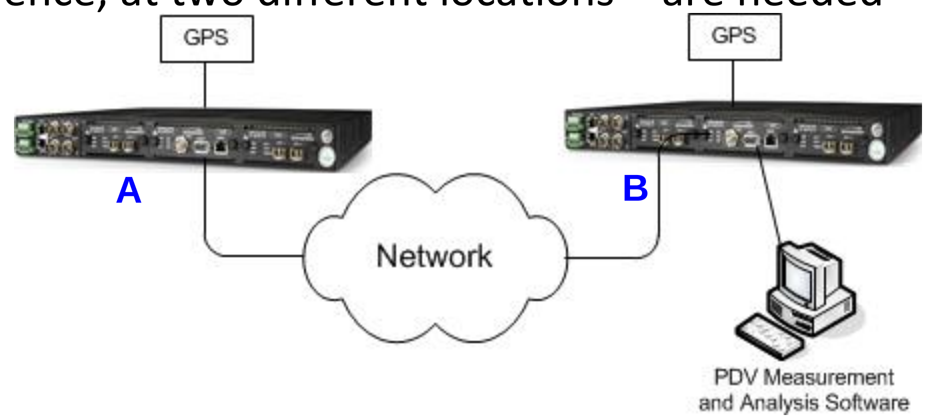
- "TIE" (Single Point Measurement)
  - Measurements are made at a single point – a single piece of equipment in a single location - a phase detector with reference - is needed





- "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	Timestamp B
F	1233166476.991204496	1233166476.991389744
R	1233166476.980521740	1233166476.980352932
F	1233166477.006829496	1233166477.007014512
R	1233166476.996147084	1233166476.995977932
F	1233166477.022454496	1233166477.022639568
R	1233166477.011771820	1233166477.011602932

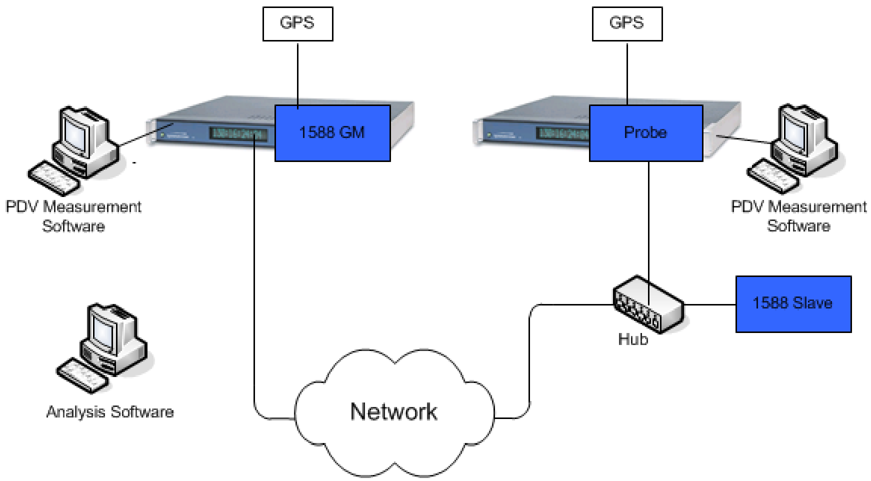


“PDV” Measurement Setup Options

Symmetricom

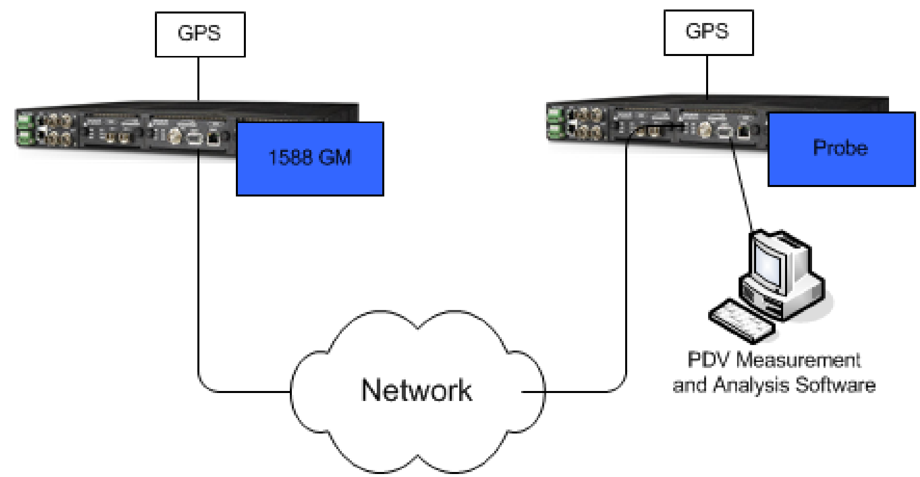
Passive Probe

(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

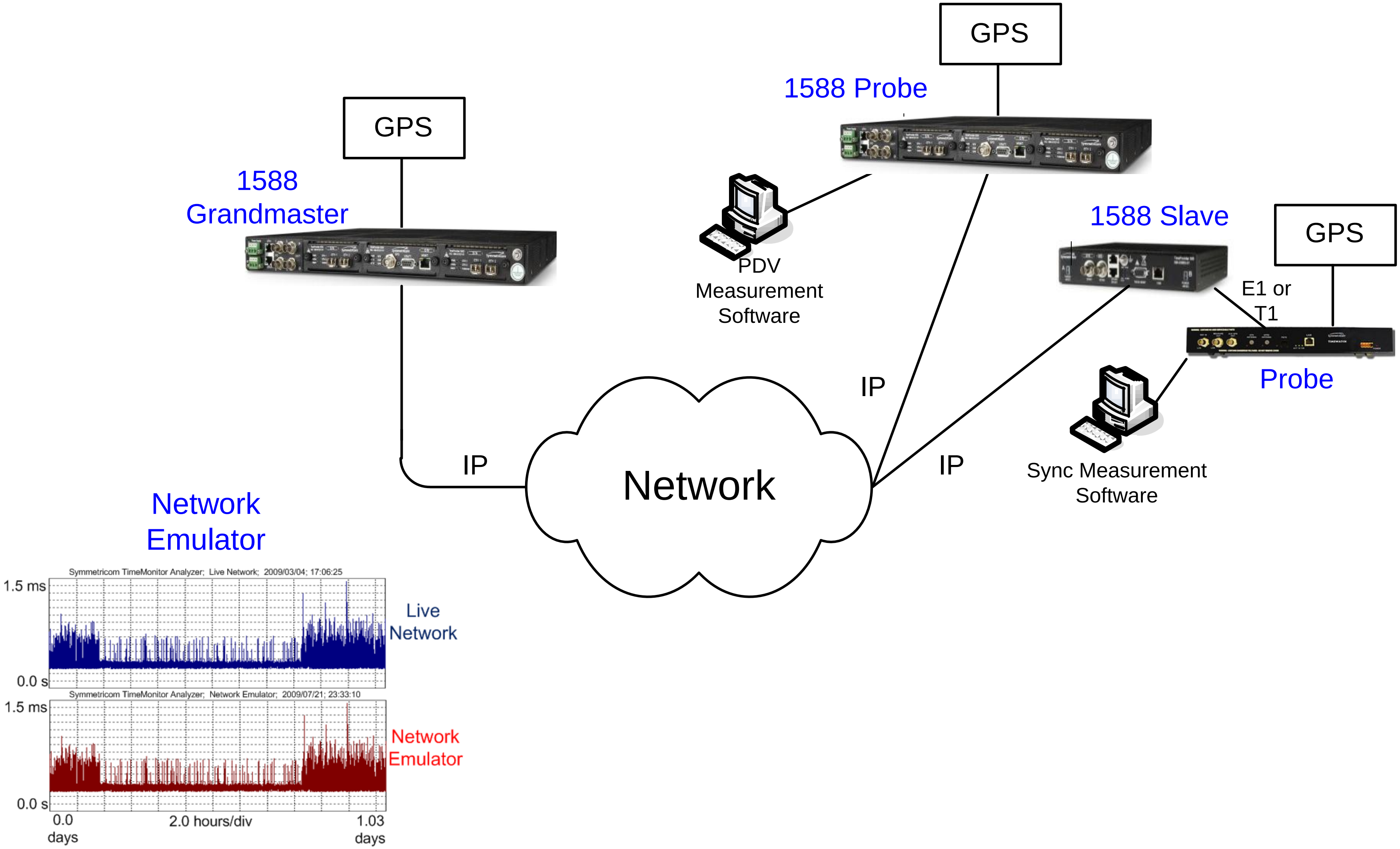


- “PDV”
  - Ideal setup - two packet timestampers with GPS reference so absolute latency can be measured as well as PDV over small to large areas
  - Alternative setup (lab) – frequency (or GPS) locked single shelf with two packet timestampers
  - Alternative setup (field) – frequency locked packet timestampers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

“TIE” and “PDV”

Symmetricom

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



PTP and NTP Probes

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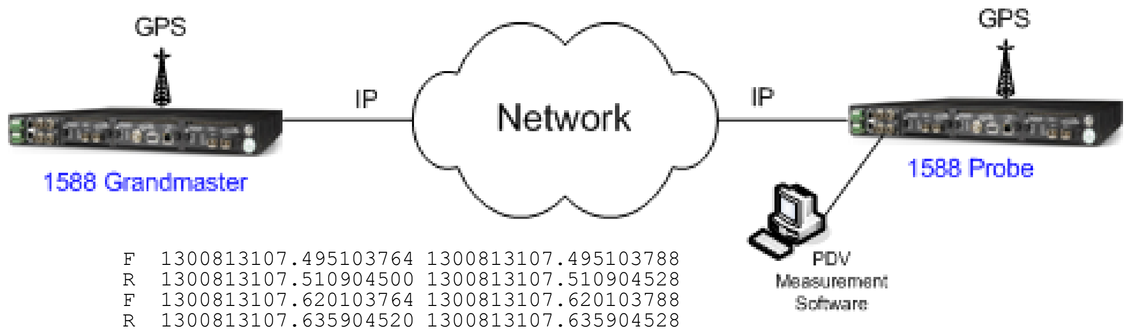
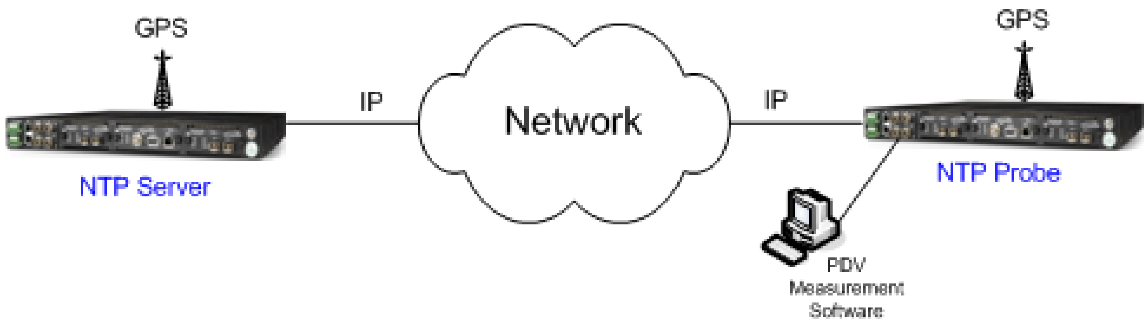
Either PTP or NTP packets can be used for probing.

- 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.



PTP

```
F  1300813107.495103764 1300813107.495103788
R  1300813107.510904500 1300813107.510904528
F  1300813107.620103764 1300813107.620103788
R  1300813107.635904520 1300813107.635904528
F  1300813107.745103764 1300813107.745103788
```



NTP

```
N,D1335140,190A968D,D1335140,190AA710,D1335140,190AD026,D1335140,190ADBF2
N,D1335140,1D0A9EB0,D1335140,1D0AA755,D1335140,1D0AD004,D1335140,1D0ADBCF
N,D1335140,210A9EB0,D1335140,210AA710,D1335140,210AD026,D1335140,210ADBAD
N,D1335140,250A9EB0,D1335140,250AA710,D1335140,250ACFBF,D1335140,250ADB46
N,D1335140,290A9EB0,D1335140,290AA710,D1335140,290AD026,D1335140,290ADBAD
```

"TIE" Analysis vs. "PDV" Analysis

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"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.

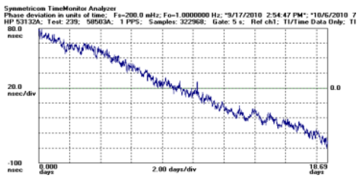
▶ The importance of raw TIE/PDV:

- 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

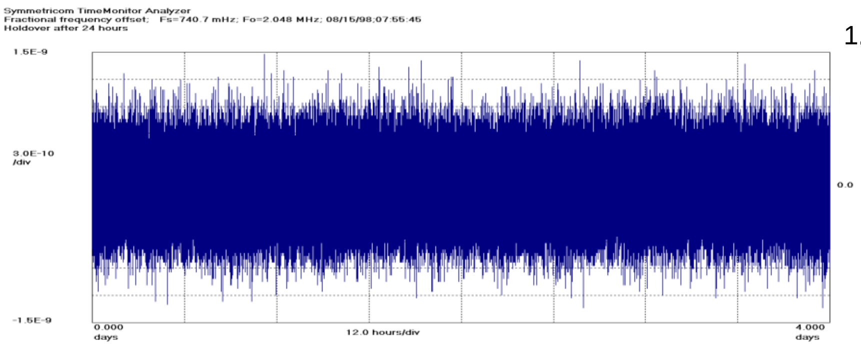


-8.97·10^-14^

Frequency Accuracy

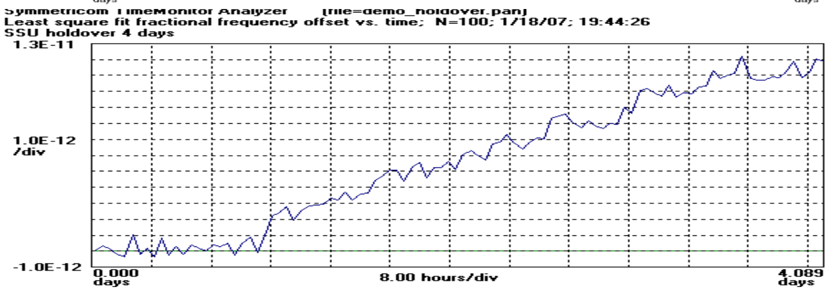
$$\omega = \frac{d\phi}{dt}$$

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



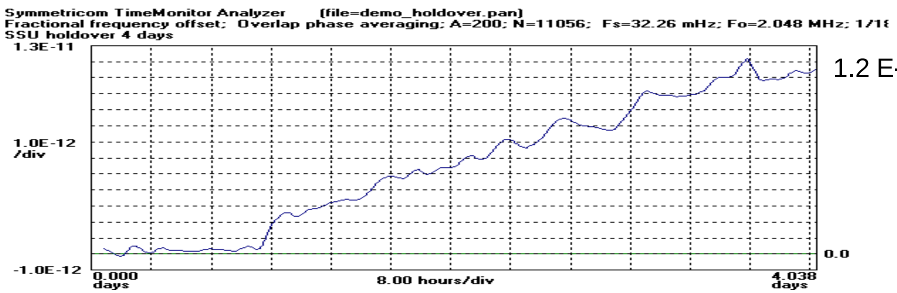
1.5 E-9

Point-by-point



1.2 E-11

Segmented LSF



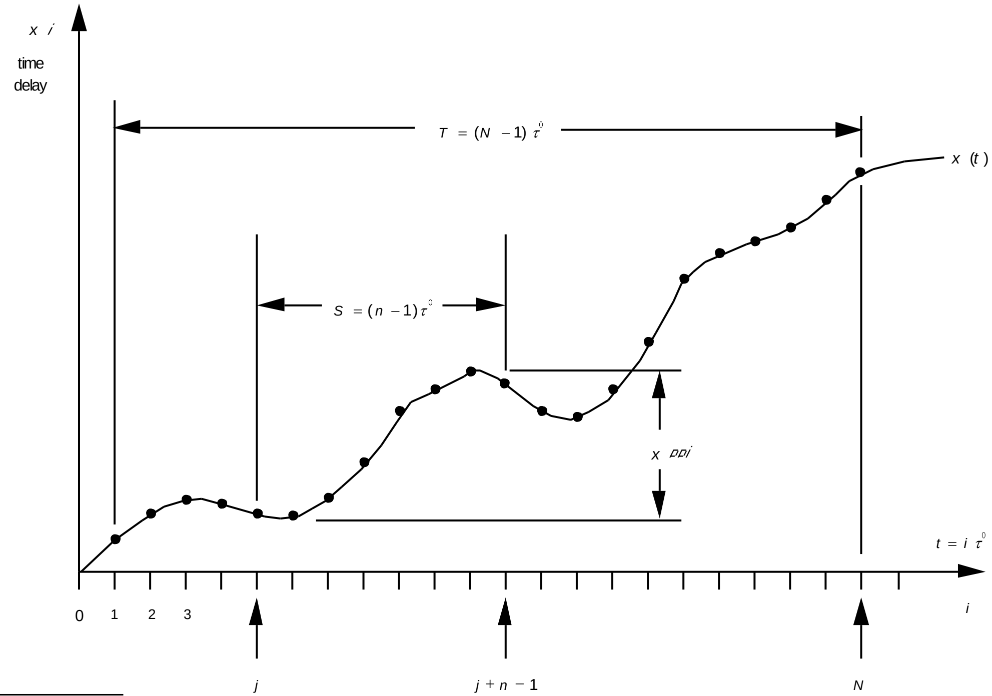
1.2 E-11

Sliding Window Averaging

Analysis from Phase: MTIE/TDEV

Symmetricom

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



MTIE is a peak detector

MTIE detects frequency offset

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

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

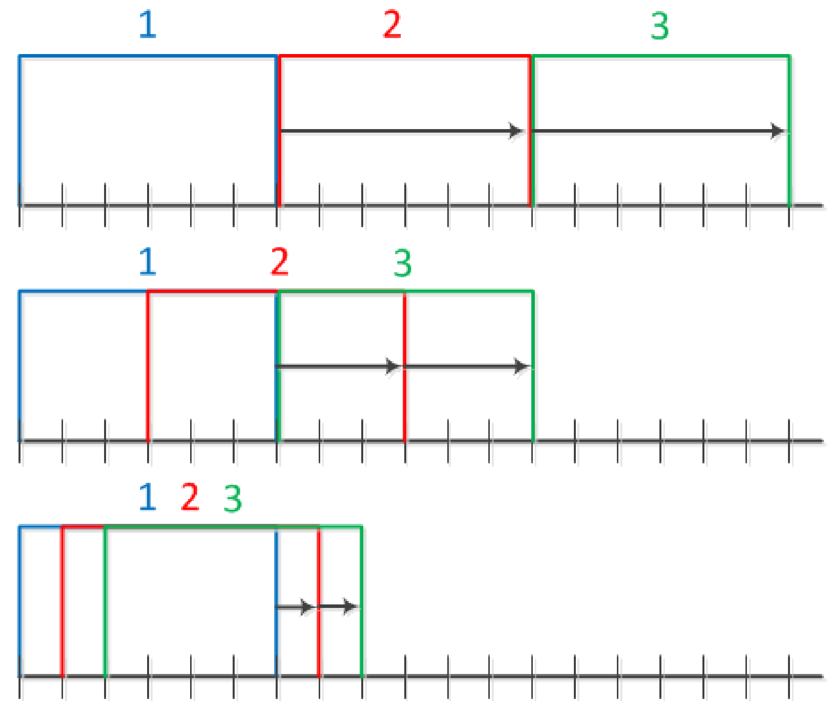
Symmetricom

- Packet Selection Processes
  1) ***Pre-processed:*** packet selection step prior to calculation
     - Example: ***TDEV***(*PDVmin*) where *PDVmin* is a new sequence based on minimum searches on the original PDV sequence
  2) ***Integrated:*** packet selection integrated into calculation
     - Example: ***minTDEV***(*PDV*)

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

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

Symmetricom

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

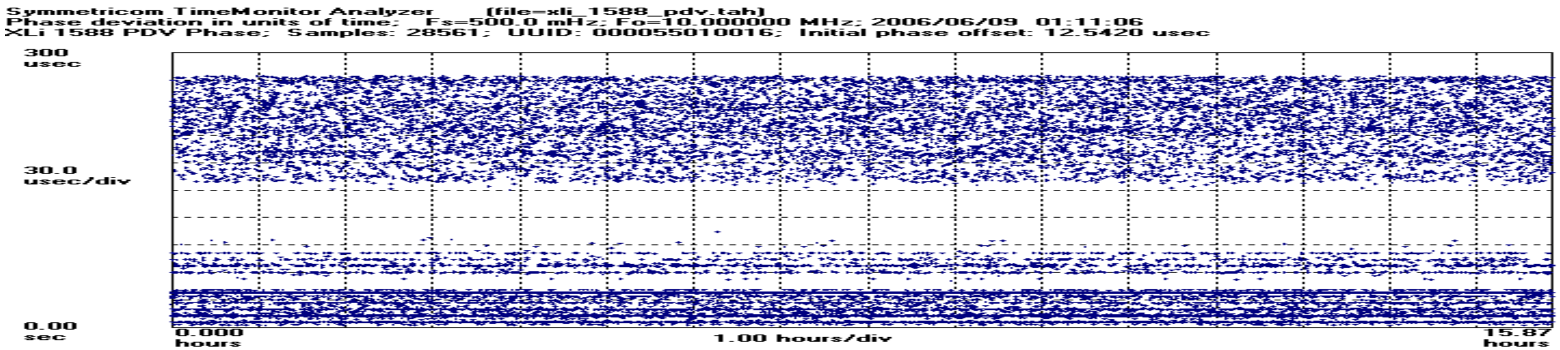
Forward

#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

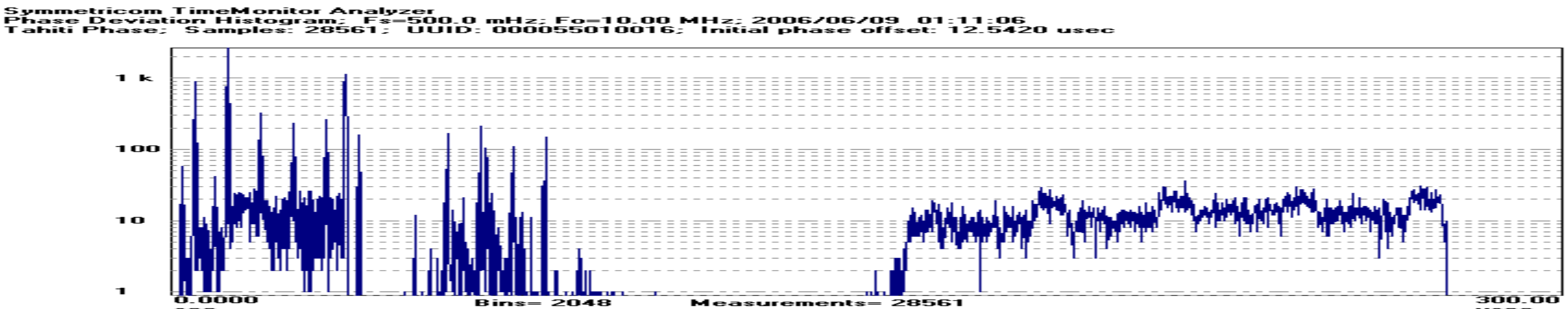
Reverse

#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



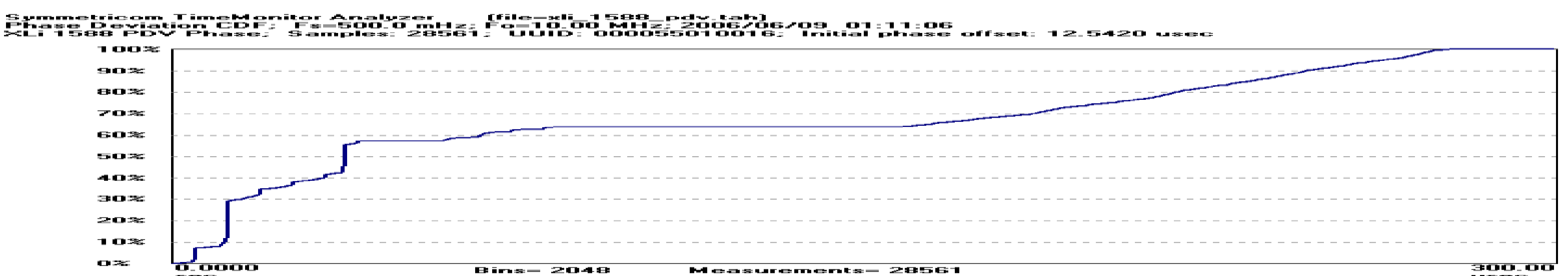
Packet Delay Sequence



PDF

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.%

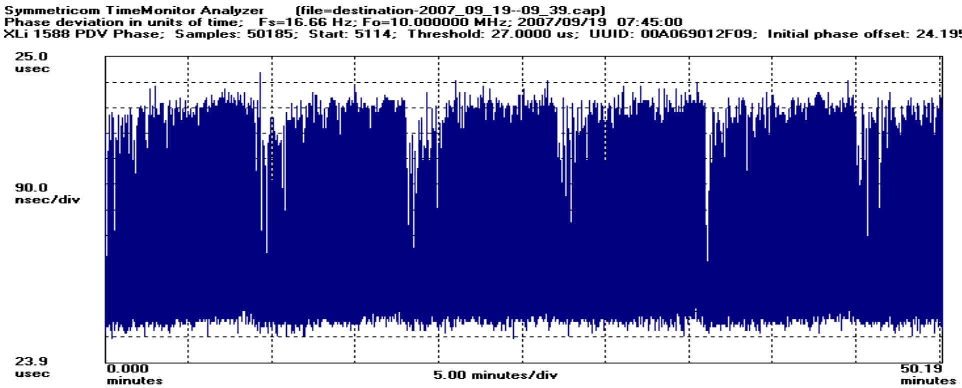
Statistics



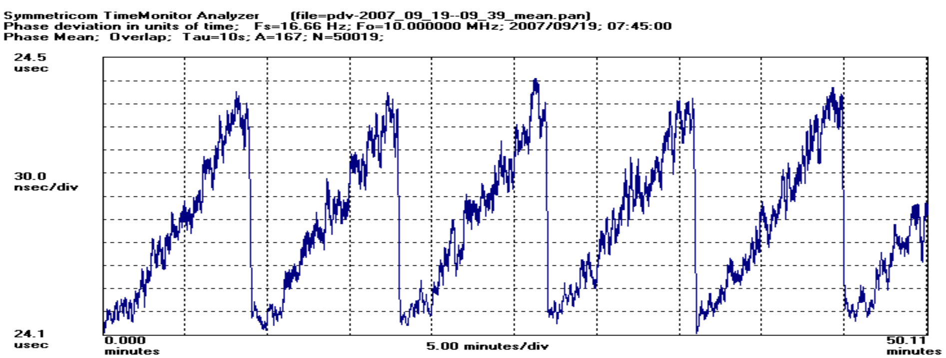
CDF

50pct: 37.65 us; 90pct: 245.5 us; 95pct: 261.9 us; 99pct: 272.3 us; 99.9pct: 274.5 us

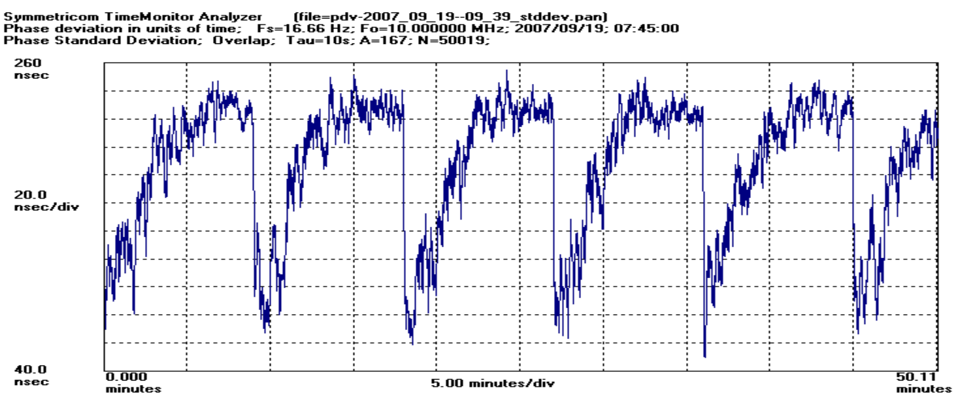
Tracked Packet Delay Statistics



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

Packet Metrics

Symmetricom

minTDEV, bandTDEV, MATIE, MAFE

TDEV

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

minTDEV

$$\sigma_{x\_min}(\tau) = \min TDEV(\tau) = \sqrt{\tfrac{1}{6}\left\langle \left[x_{\min}(i+2n) - 2x_{\min}(i+n) + x_{\min}(i) \right]^2 \right\rangle} \quad x_{\min}(i) = \min\lfloor x_j \rfloor for(i <= j <= i+n-1)$$

bandTDEV

$$\sigma_{x\_band}(\tau) = bandTDEV(\tau) = \sqrt{\tfrac{1}{6}\left\langle \left[x'_{band\_mean}(i+2n) - 2x'_{band\_mean}(i+n) + x'_{band\_mean}(i) \right]^2 \right\rangle} \quad x'_{band\_mean}(i) = \tfrac{1}{m}\sum_{j=a}^{b} x'_{j+i}$$

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

$$MATIE(n\tau_0) \cong \max_{1 \le k \le N-2n+1} \frac{1}{n} \left| \sum_{i=k}^{n+k-1} (x_{i+n} - x_i) \right|$$

, n = 1, 2, ..., integer part (N/2)

MAFE

$$MAFE(n\tau_0) = \frac{MATIE(n\tau_0)}{n\tau_0}$$

minMAFE

$$\min MAFE(n\tau_0) \cong \frac{\max\limits_{1 \le k \le N-2n+1} \left| \sum_{i=k}^{n+k-1} \left(x_{\min}(i+n) - x_{\min}(i) \right) \right|}{n\tau_0}$$

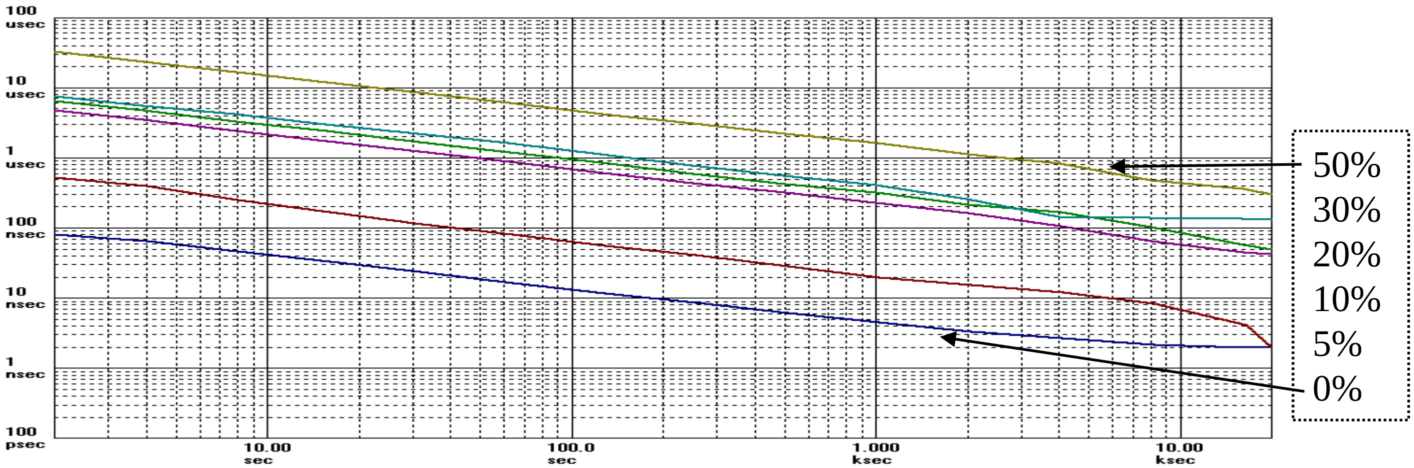
where n = 1, 2, ..., integer part (N/2) and where

$$x_{\min}(i) = \min\lfloor x_j \rfloor for(i <= j <= i+n-1)$$

Reference: ATIS-0900003.2010 Technical Report: *Metrics Characterizing Packet-Based Network Synchronization*, Oct. 2010.

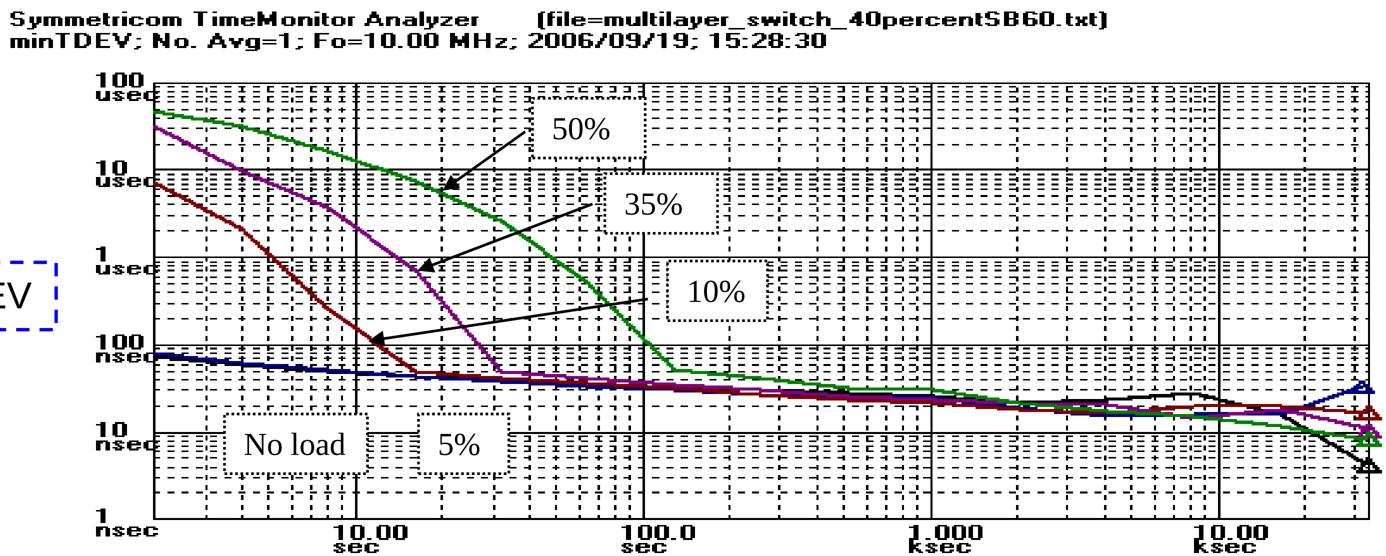
TDEV & minTDEV with Traffic

TDEV



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

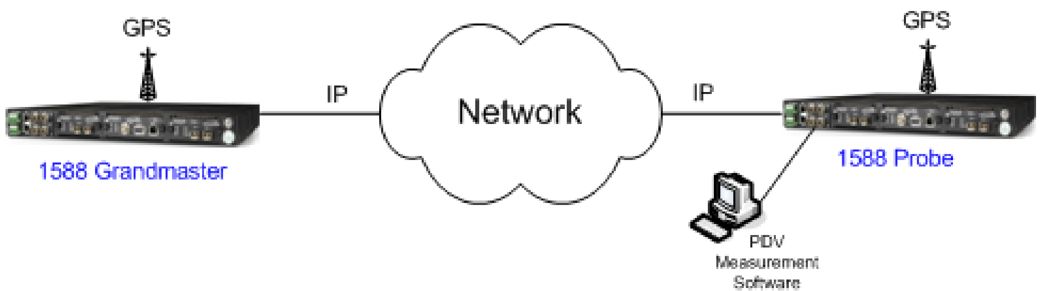
minTDEV

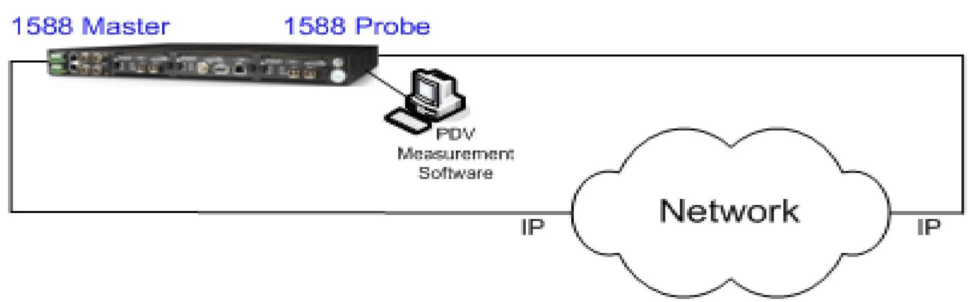


Packet Time Transport

"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

Symmetricom

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

```
#Start: 2010/03/06 17:15:30
0.0000,   1.47E-6,   1.11E-6
0.1000,   1.54E-6,   1.09E-6
0.2000,   1.23E-6,   1.12E-6
0.3000,   1.40E-6,   1.13E-6
0.4000,   1.47E-6,   1.22E-6
0.5000,   1.51E-6,   1.05E-6
```

Minimum Search Sequence

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

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		

Metrics: Time Transport

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

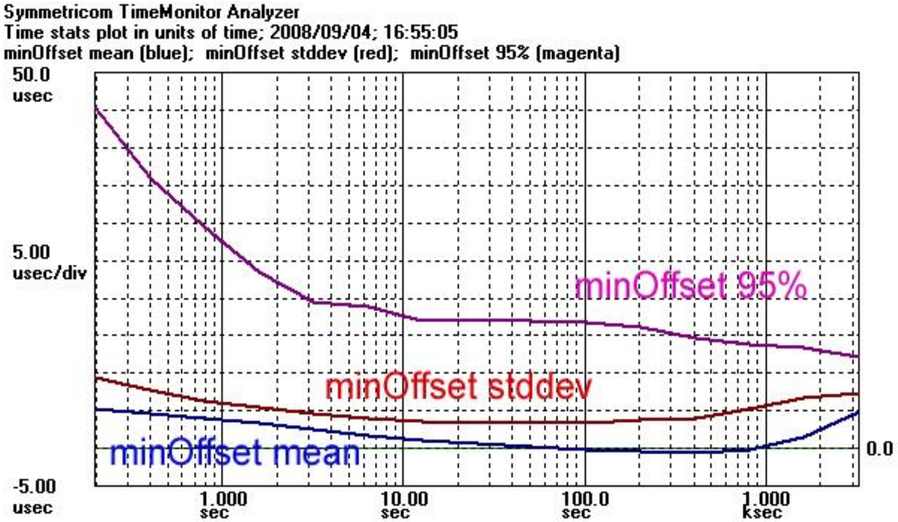
minTDISP (minimum time dispersion): minOffset {y} plotted against minRoundtrip {x} as a scatter plot

minOffset statistics: minOffset statistic such as mean, standard deviation, or 95 percentile plotted as a function of time window tau

Metrics: Time Transport

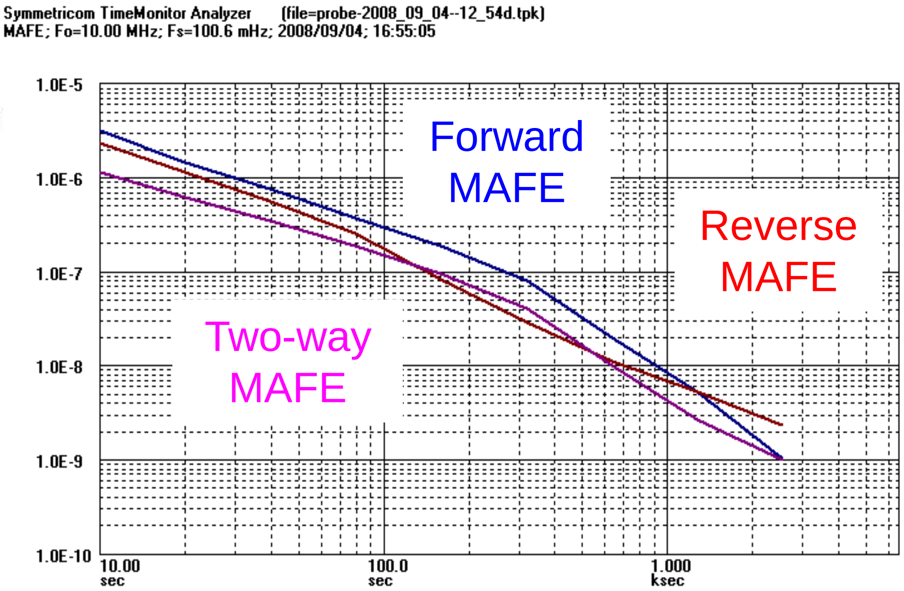
minOffset Statistics

(Two-way minimum offset statistics vs. τ)



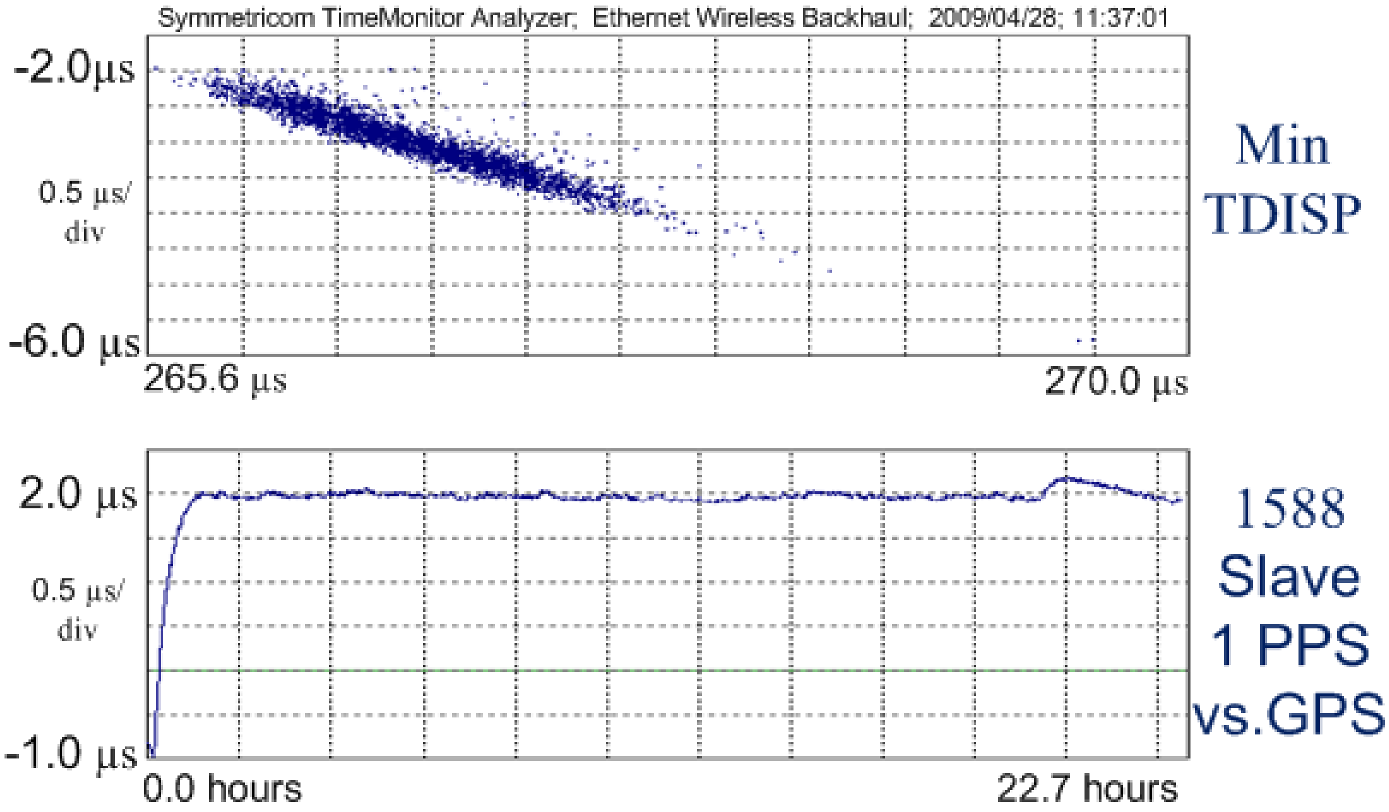
Two-way MAFE

(MAFE of minOffset)



Asymmetry in Wireless Backhaul

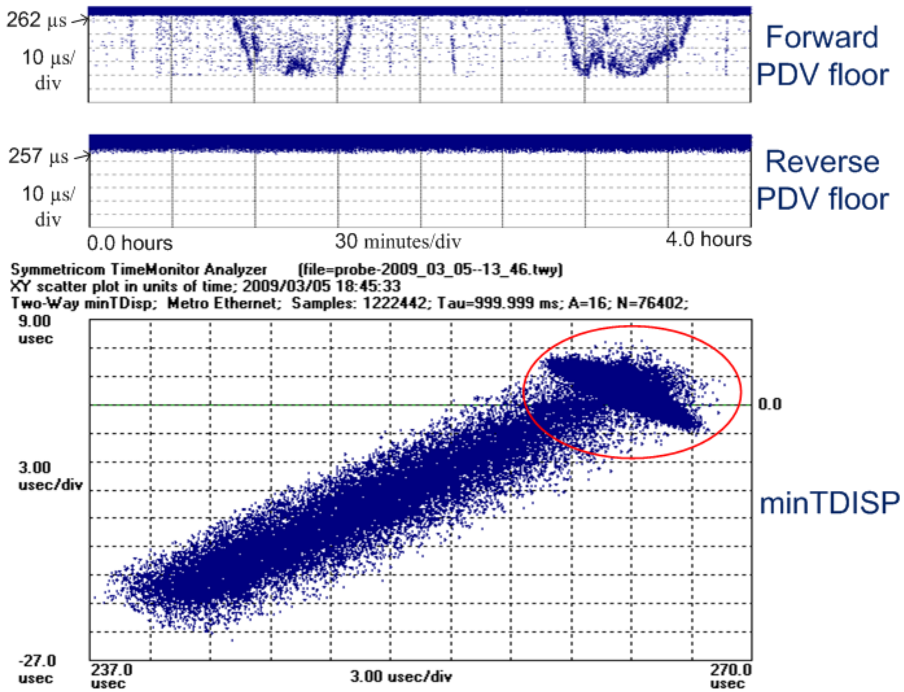
(Ethernet wireless backhaul asymmetry and IEEE 1588 slave 1PPS under these asymmetrical network conditions)



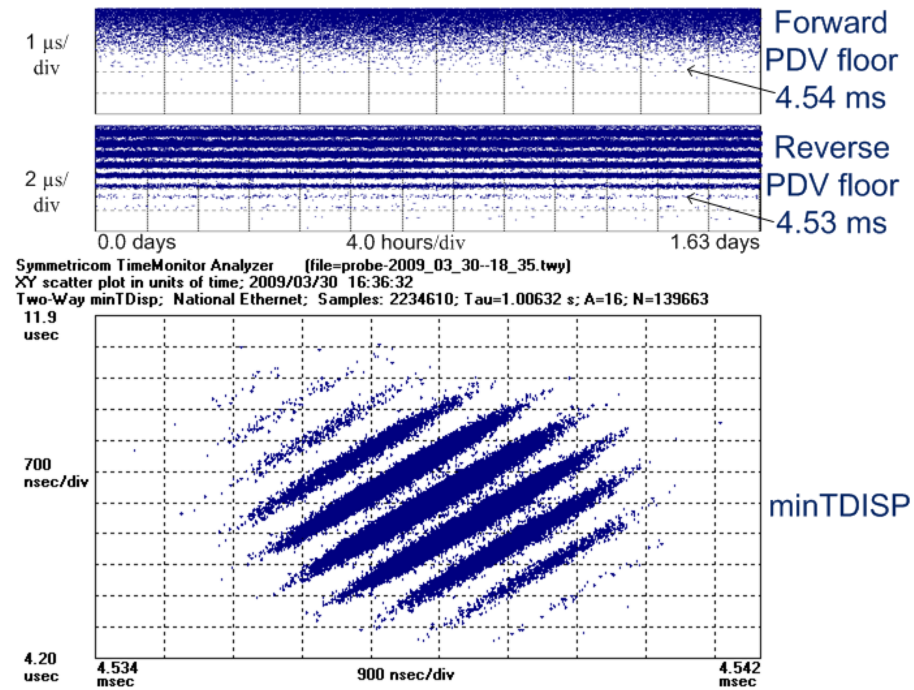
Case Studies

Symmetricom

Metro Ethernet Network



National Ethernet Network

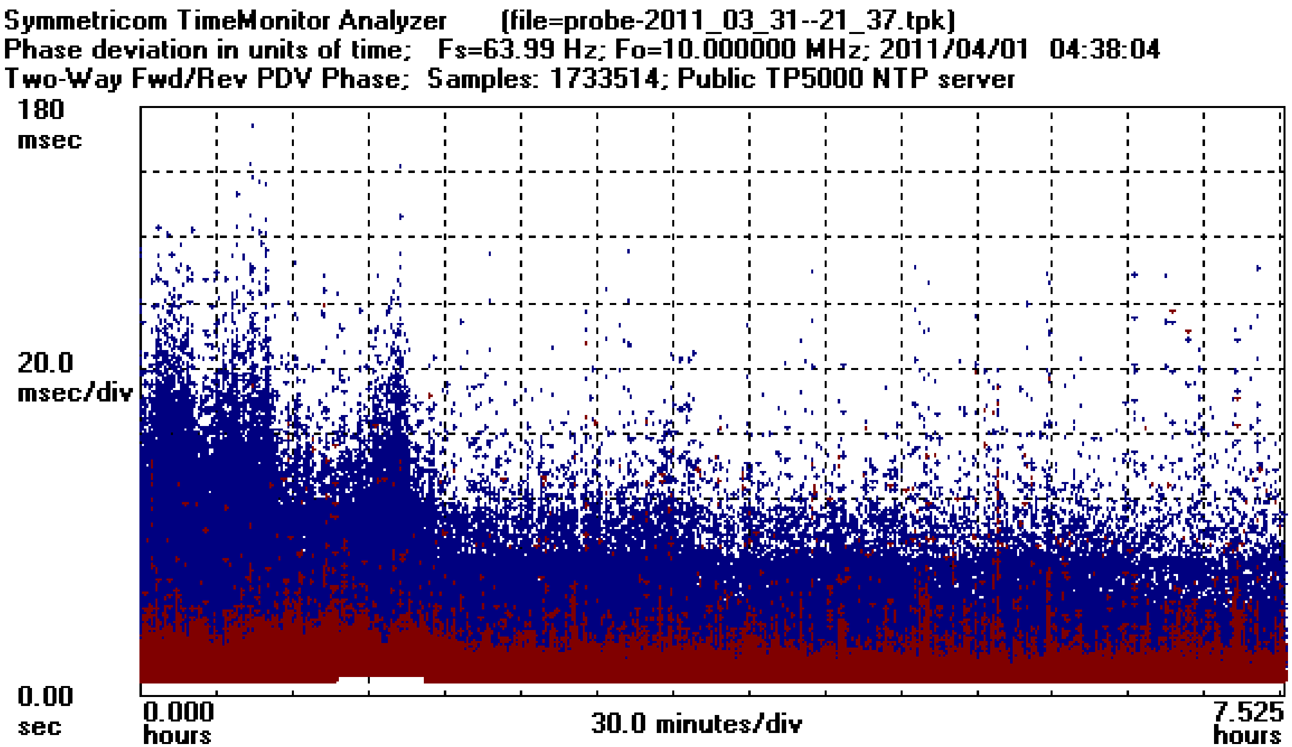


Forward and reverse packet delay sequences with zooms into the respective floors and minTDISP

Case Studies

Symmetricom

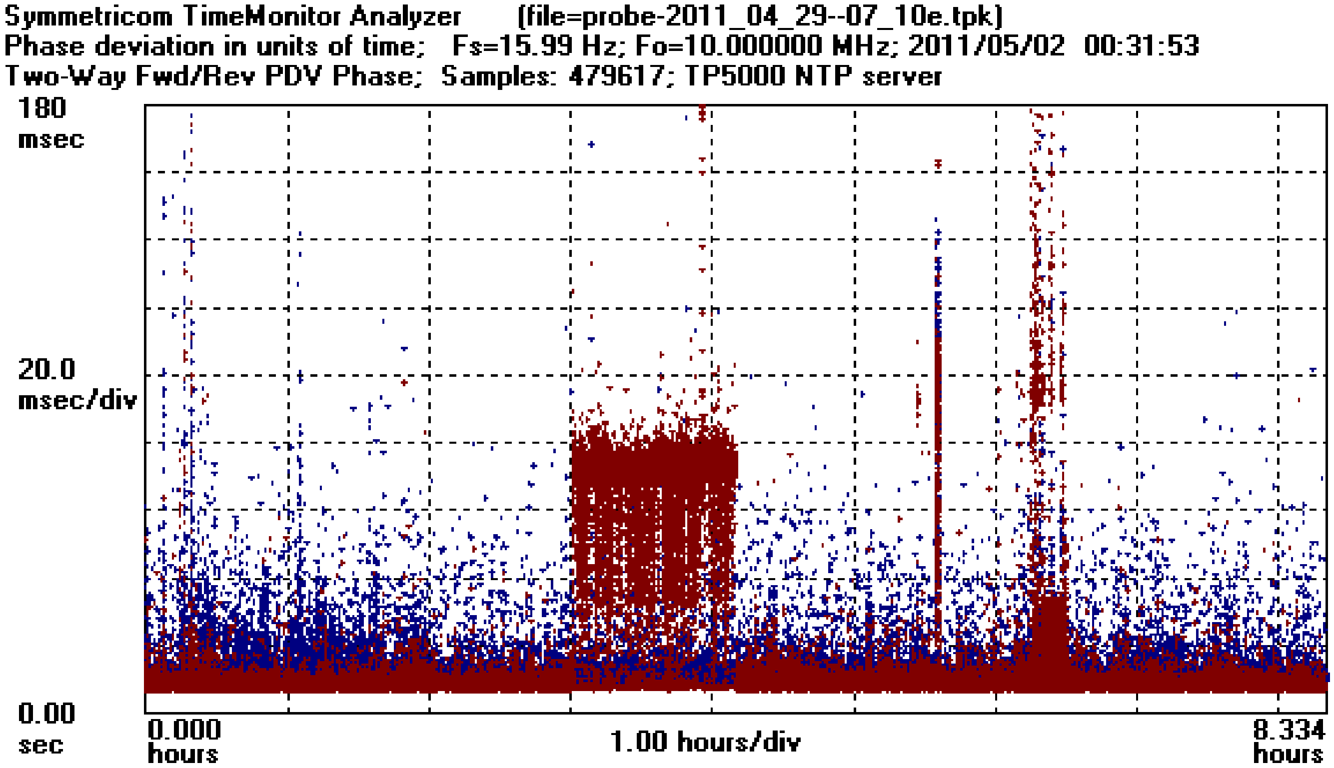
Public Internet w/ Cable Modem Access (NTP probe)



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

Symmetricom

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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