Bringing Expertise Into Focus

Packet Network Timing Measurements, Metrics, and Analysis

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Your Network. Optimized.

Presentation Outline

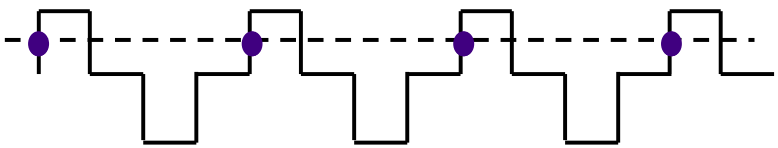
- Introduction
  - Types of measurements:
    1. Synchronization “TIE”
    2. Packet “PDV”
    3. Packet “Load”
  - Measurement equipment overview
- Synchronization and Packet Analysis
  - TIE and PDV based metrics
  - Packet selection processes and methods
  - Frequency transport metrics
  - Time transport metrics
- Network Measurements
  - Lab/production packet network measurements
  - Linking packet delay metrics to sync performance
- Load Probe
  - Load probe measurement theory
  - “Load” and “PDV” measurement relationship
  - Network load probe measurements

"TIE" vs. "PDV"

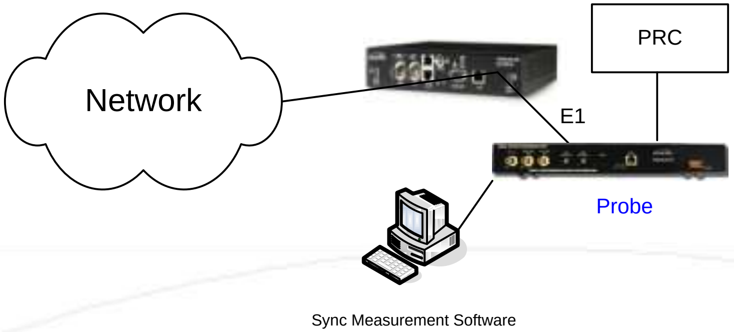
- "TIE" vs "PDV"
  - Traditional TDM synchronization measurements: signal edges are timestamped producing a sequence of samples
  - Packet timing measurements: packet departure/arrival times are sampled and packet delay sequences are formed
  - Both require (1) PRC/GPS; (2) Precision HW timestamping; (3) PC + SW
- Measurement equipment:
  - TIE: Counters, TIA's, Test-sets, BITS, SSU, GPS receivers
  - PDV: IEEE 1588 probes, NTP probes, network probes
  - Load: Load probe
- 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

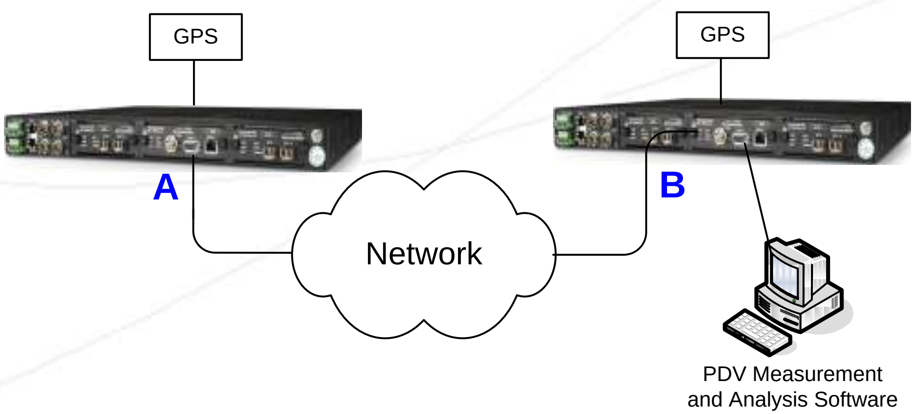


0 µs 1.001 µs 1.997 µs 3.005 µs



- "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

	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

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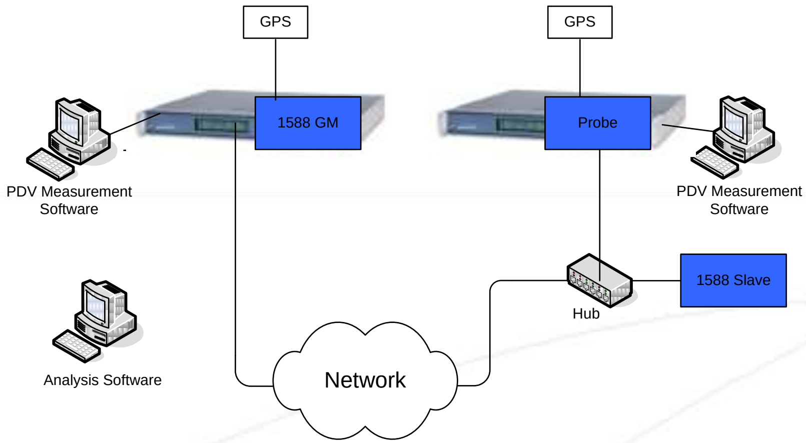
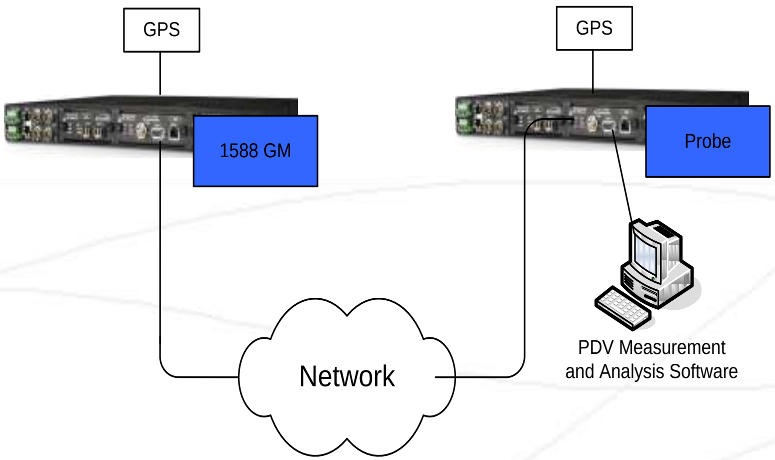
Passive Probe

(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” and “Load”

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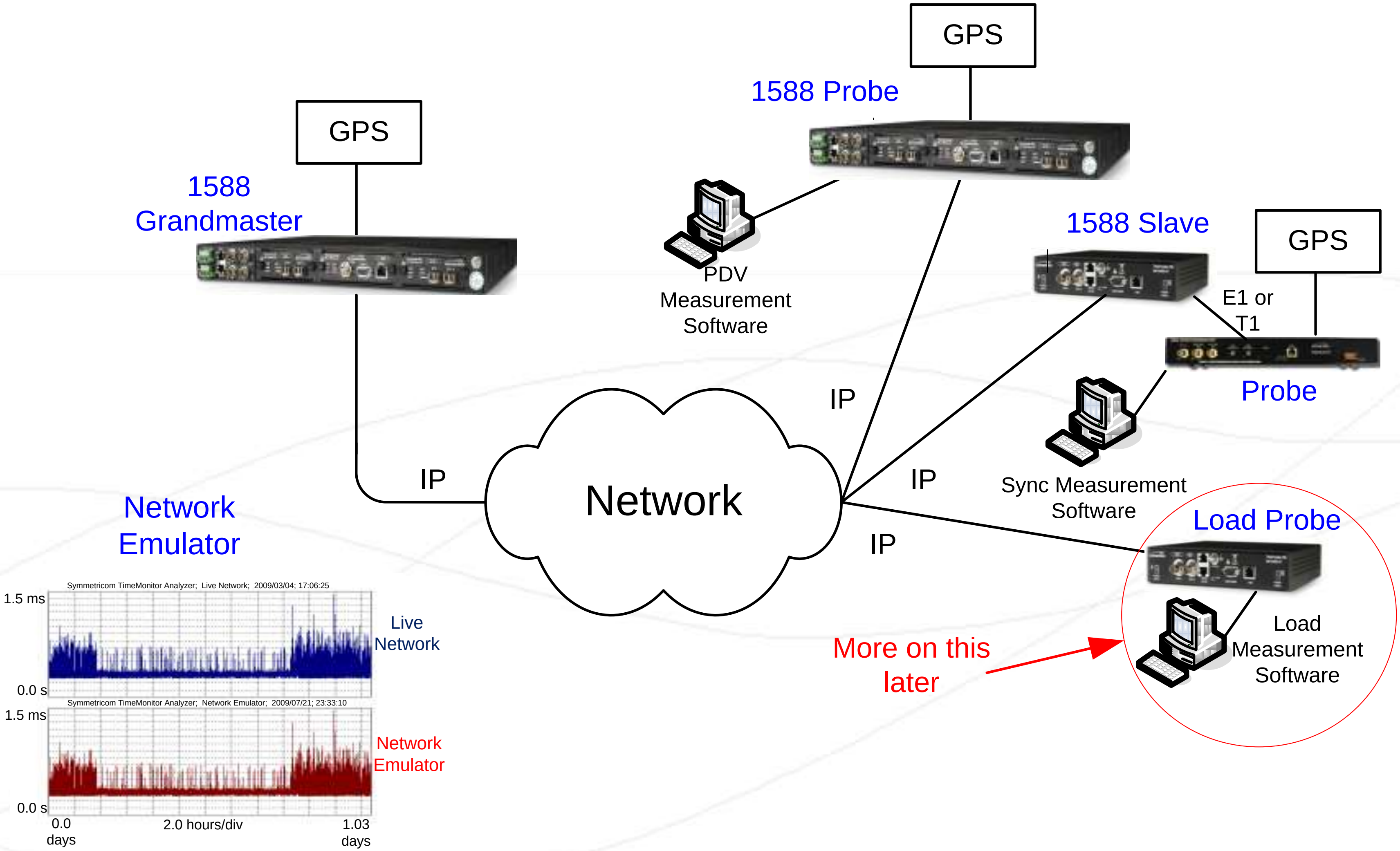
In most packet network measurement setups, both “TIE” and “PDV” are measured at the same time



"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

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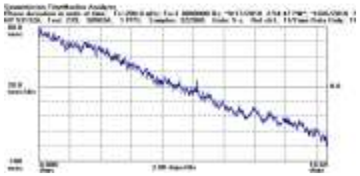
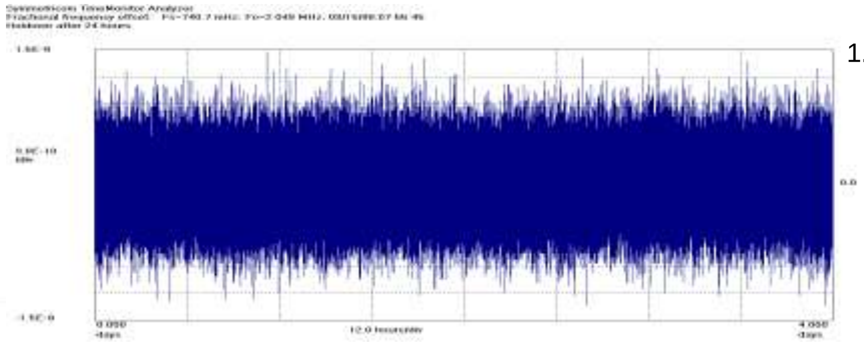


-8.97·10^{-14}

Frequency Accuracy

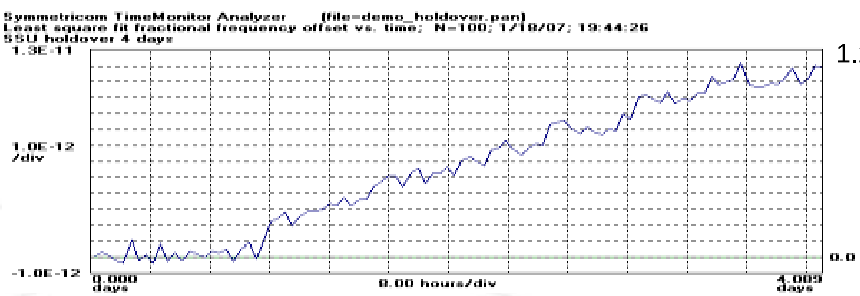
$$\omega = \frac{d\phi}{dt}$$

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



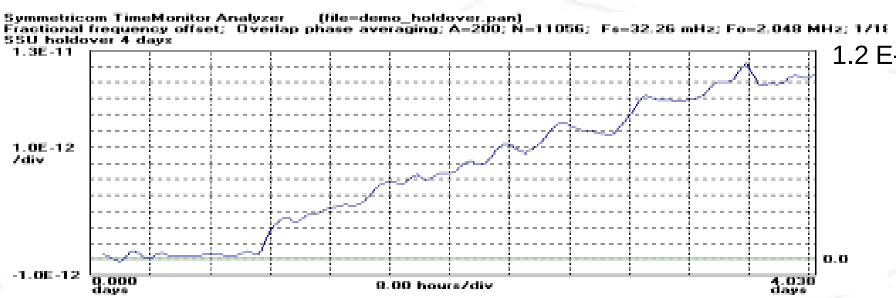
1.5 E-9

Point-by-point



1.2 E-11

Segmented LSF



1.2 E-11

Sliding Window Averaging

Analysis from Phase: MTIE/TDEV

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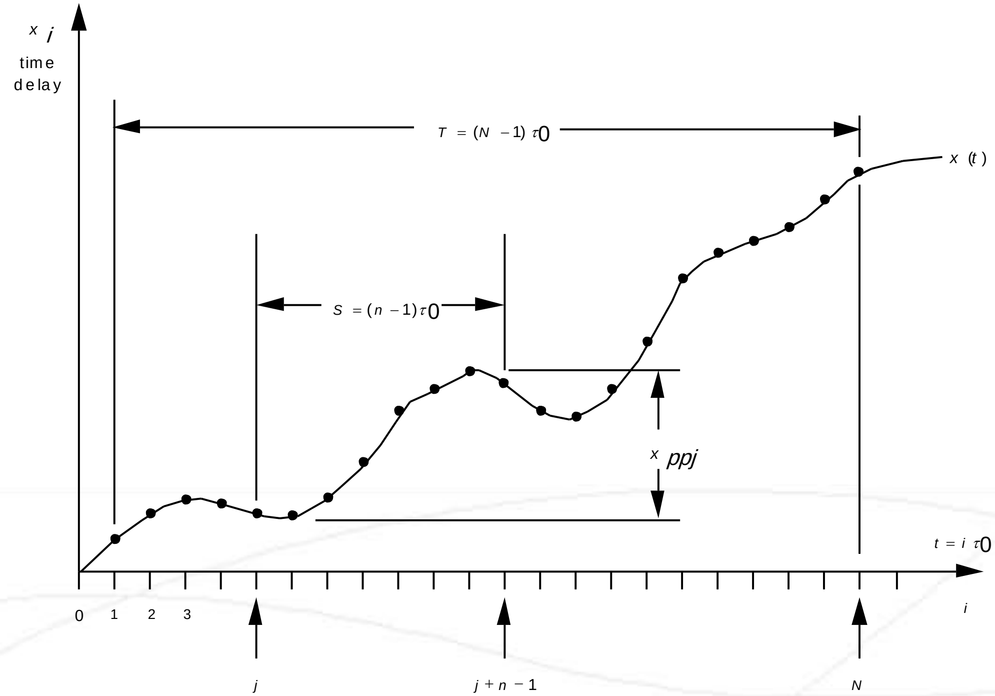
$$MTIE(S) = \max_{j=1}^{N-n+1}\left[\max_{i=j}^{n+j-1}(x_i) - \min_{i=j}^{n+j-1}(x_i)\right]$$



MTIE is a peak detector
MTIE detects frequency offset

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

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***(*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: $x(n\tau_0) = \dfrac{\sum_{i=0}^{(K-1)} w((nK+i)\tau_P)\cdot\phi(n,i)}{\sum_{i=0}^{(K-1)}\phi(n,i)}$ $\quad \phi(n,i) = \begin{cases} 1 & for \quad |w(nK+i)-\alpha(n)| < \delta \\ 0 & otherwise \end{cases}$

Packet Delay Sequence

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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

Reverse

#Start: 2009/10/06 15:10:30

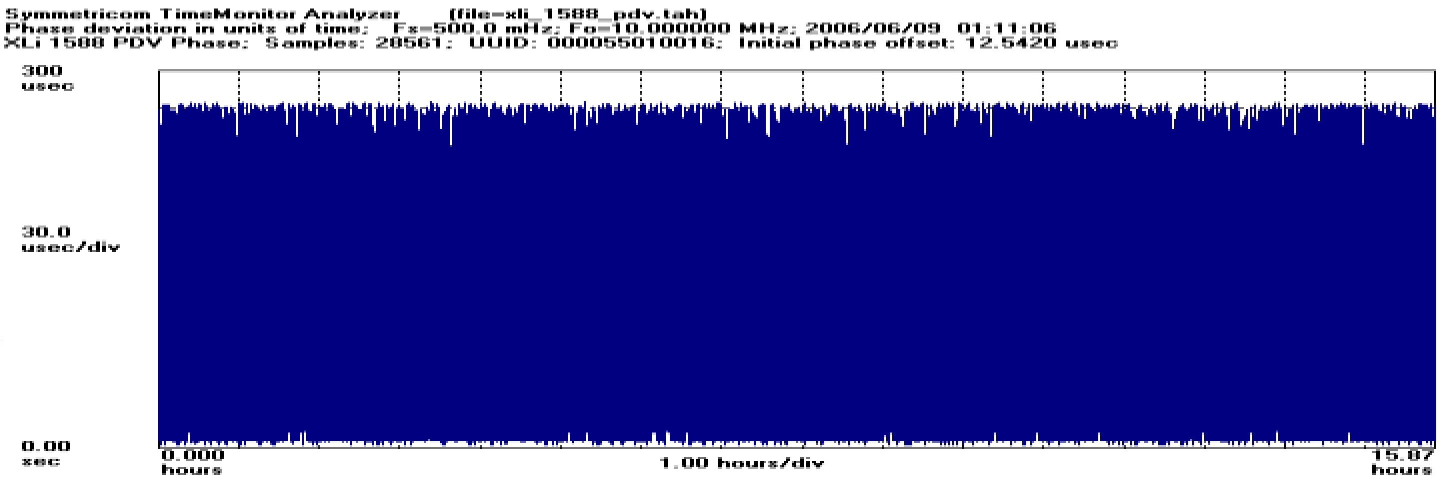
0.0000,	2.473E-3
0.0155,	2.330E-3
0.0312,	2.273E-3
0.0467,	2.258E-3
0.0623,	2.322E-3

#Start: 2009/10/06 15:10:30

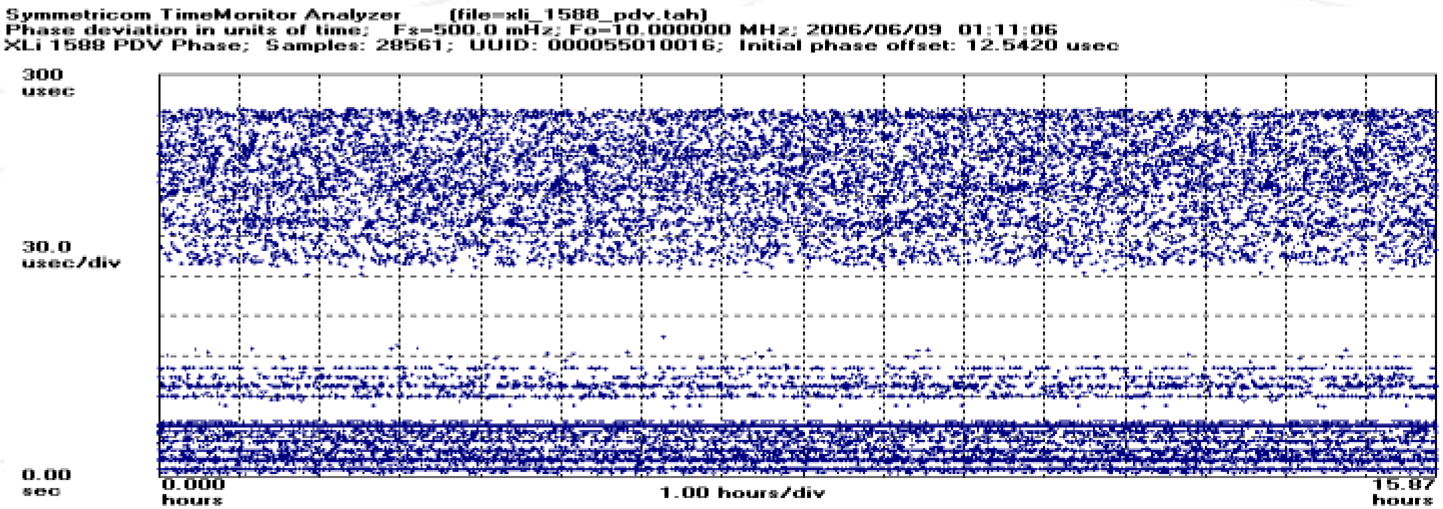
0.0000,	3.334E-3
0.0153,	2.913E-3
0.0311,	2.826E-3
0.0467,	2.968E-3
0.0624,	3.065E-3

Packet Delay Sequence

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



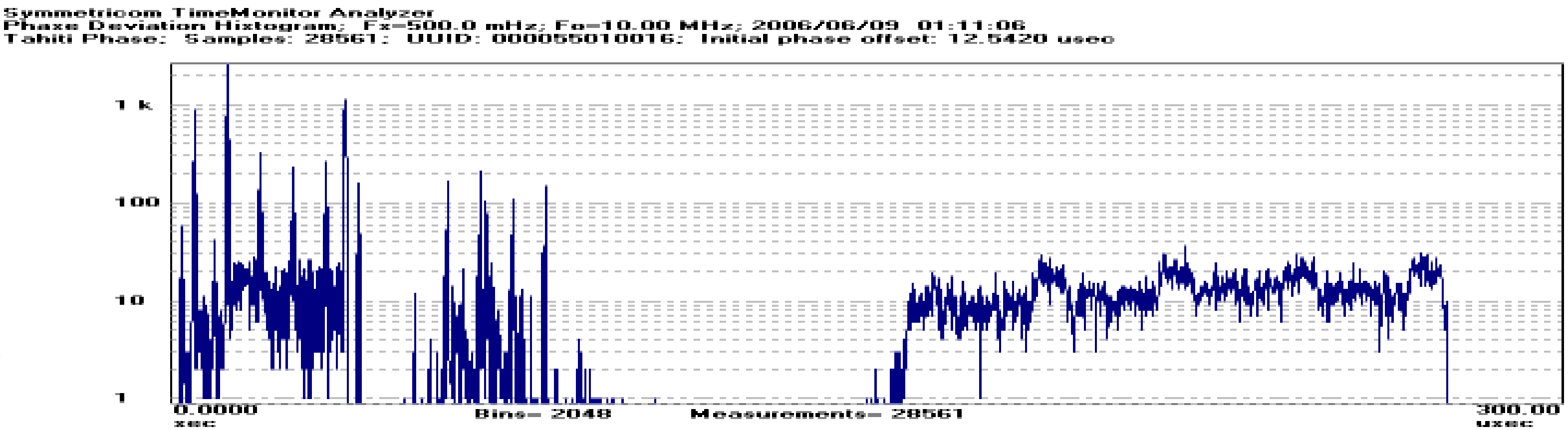
Measurement points connected



Measurement points as discrete dots

Packet Delay Distribution

Packet Delay Distribution

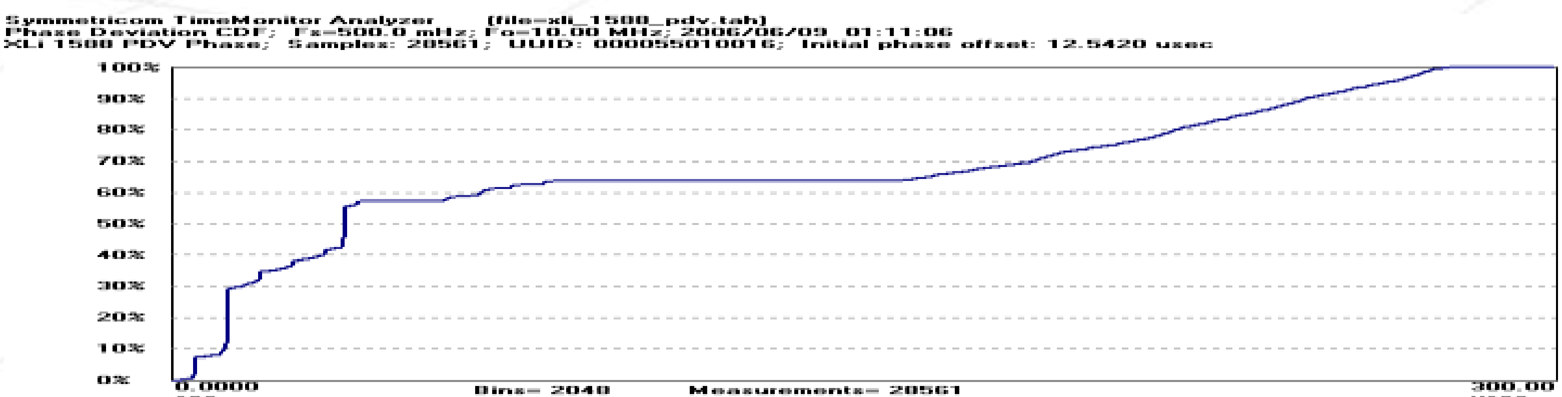


PDF

Minimum: 1.904297 usec
Maximum: 275.2441 usec
Peak to Peak: 273.3 usec

Mean: 96.71927 usec
Standard Deviation: 97.34 usec
Population: 28561
Percentage: 100.%

Statistics



CDF

Tracked Packet Delay Statistics

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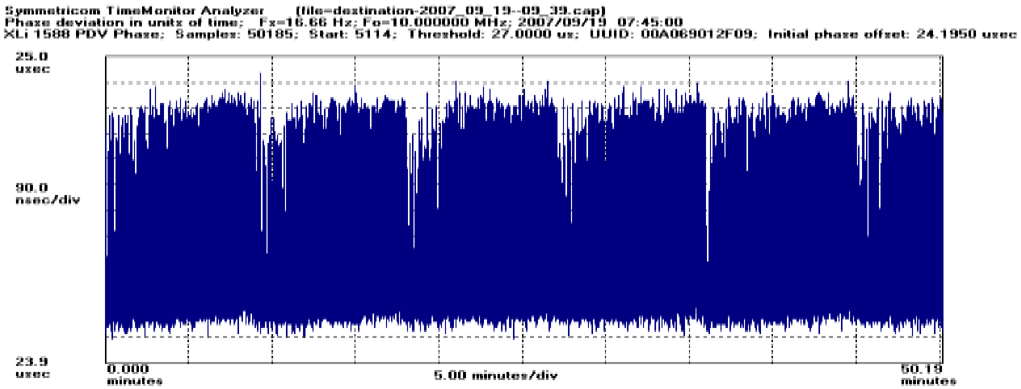
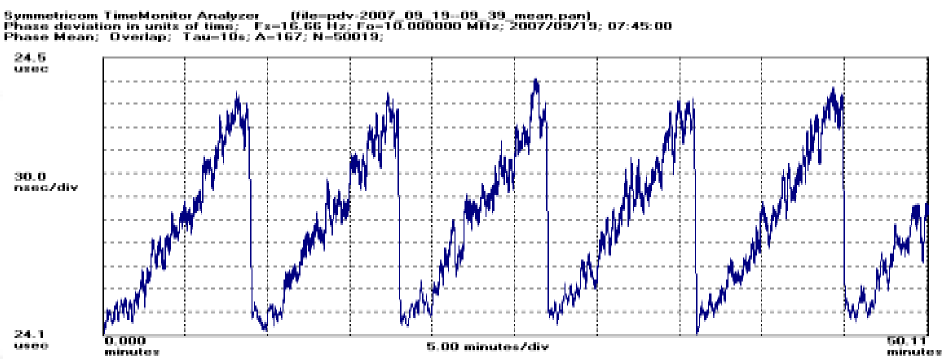
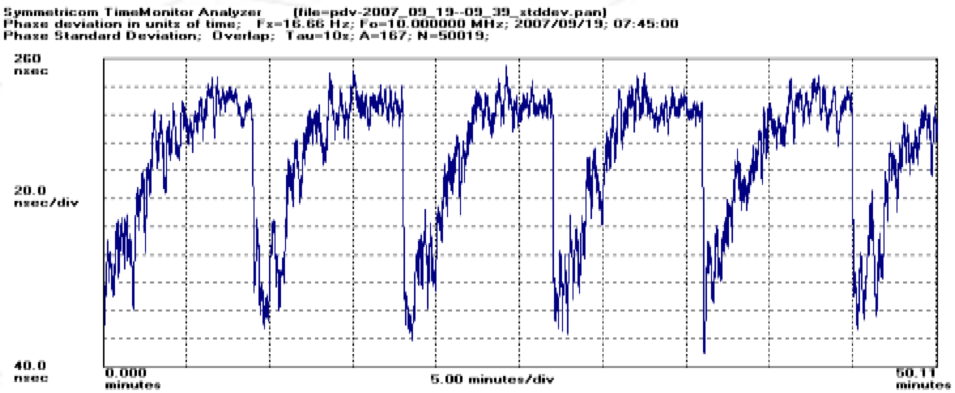


Raw packet delay appears relatively static over time



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

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

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: *Maximum Average Time Interval Error*, WD 60, Nokia-Siemens Networks, ITU-T Q13/15, Rome, Sep. 2008.

minTDEV & bandTDEV

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

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

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

To define 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 ≤ j ≤ 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 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

References: *Definition of Minimum TDEV (minTDEV),* WD 27, ITU-T Q13/15, Geneva, June 2007
Definition of BandTDEV, Symmetricom, WD 68, ITU-T Q13/15, Rome, Sep. 2008.

TDEV & minTDEV with Traffic

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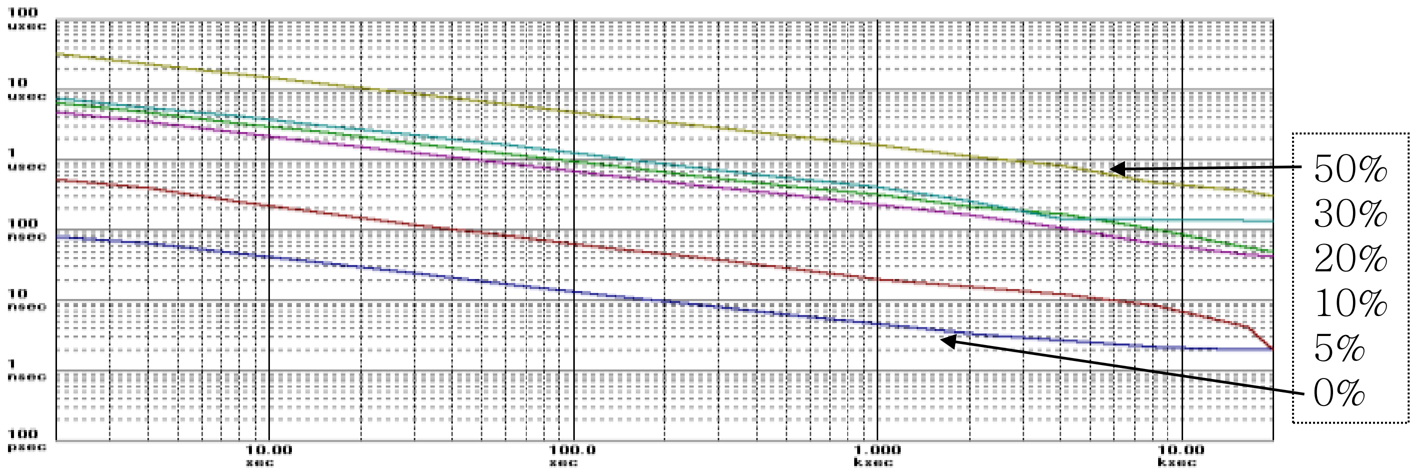
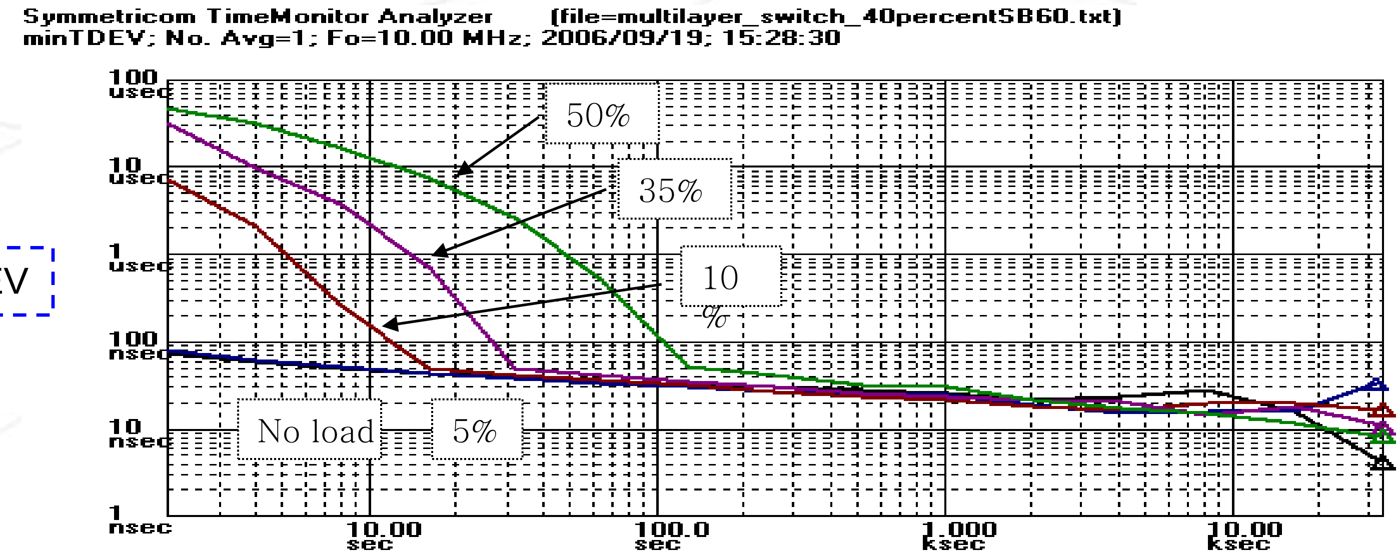
TDEV

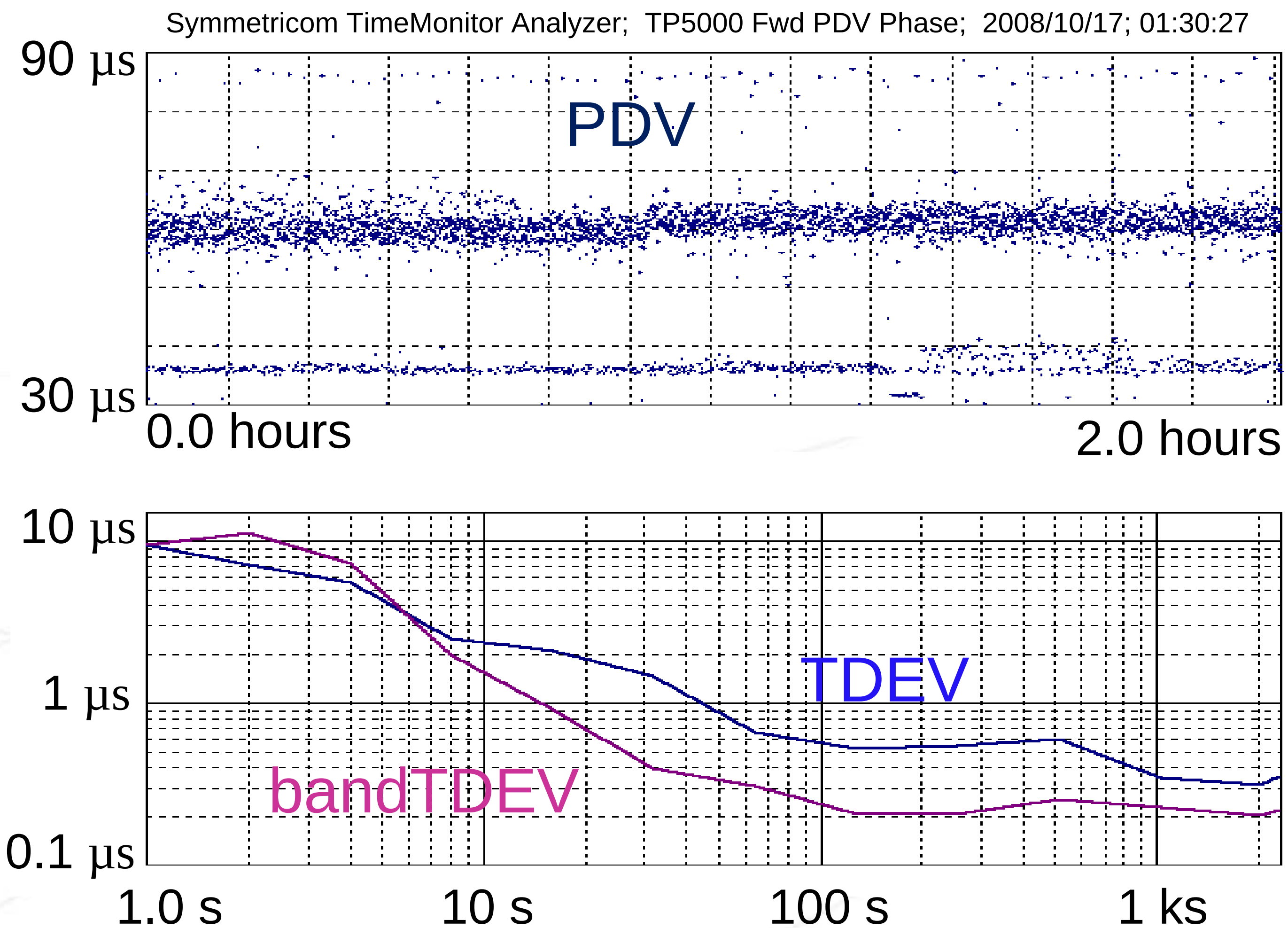


Lower levels of noise with the application of a MINIMUM selection algorithm
minTDEV at various traffic levels on a switch (0% to 50%) converge

minTDEV



bandTDEV Calculation



Metrics: Time Transport

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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

#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

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

Metrics: Time Transport

Packet Time Transport Metrics

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

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

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

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

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

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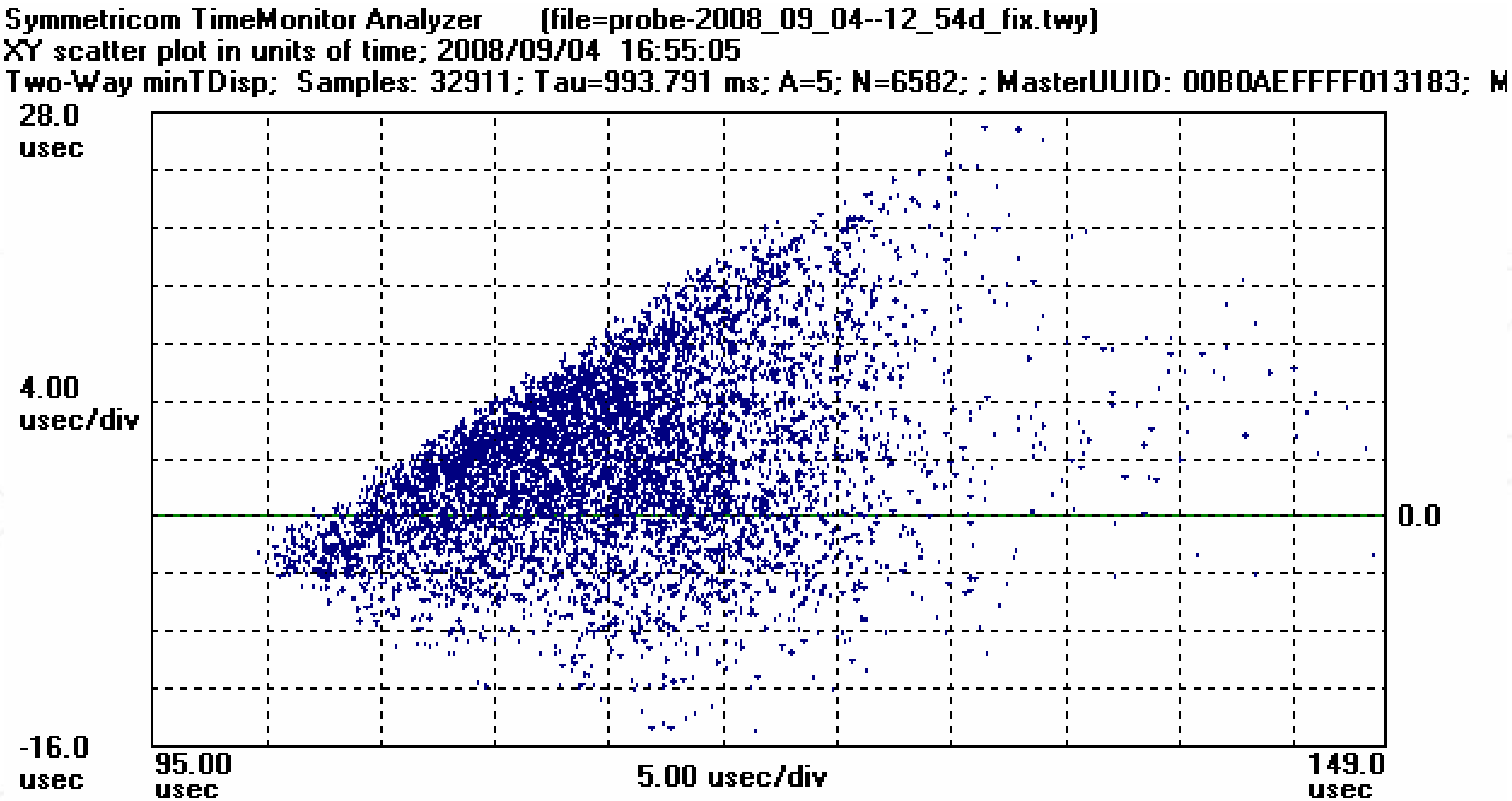
minTDISP

(minOffset vs. minRoundtrip)



Metrics: Time Transport

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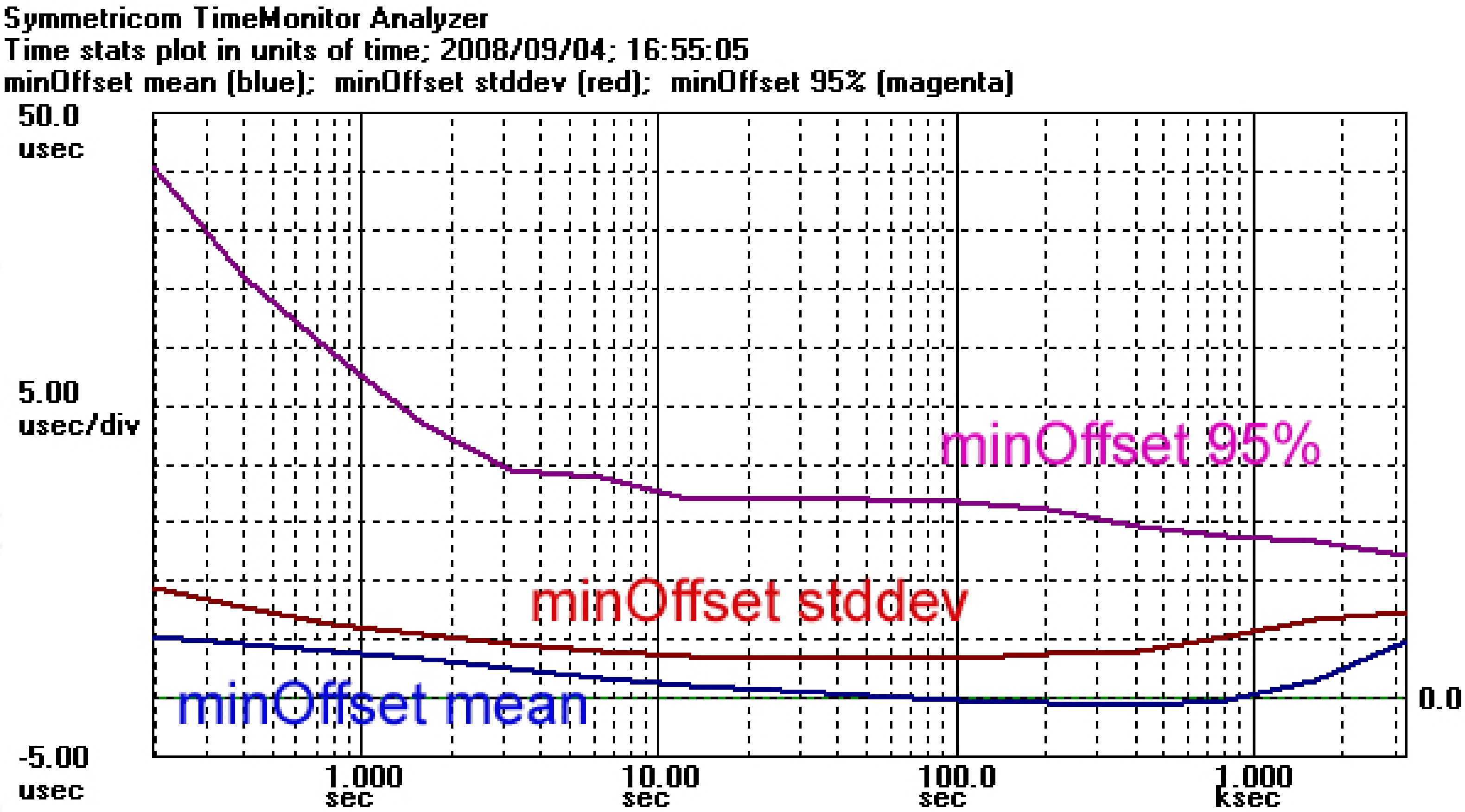
minOffset Statistics

(Two-way minimum offset statistics vs. τ)



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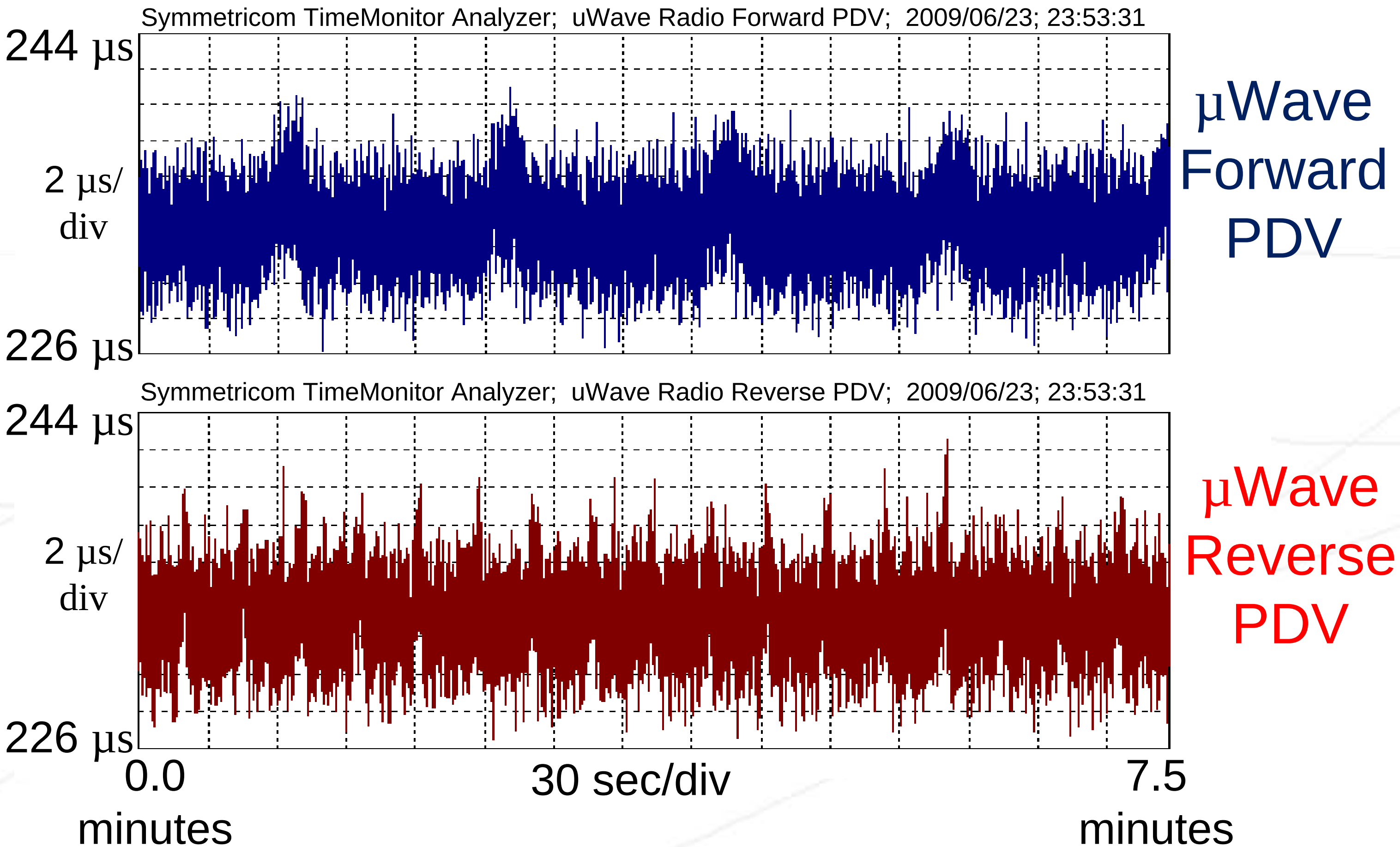
Asymmetry in Microwave Transport

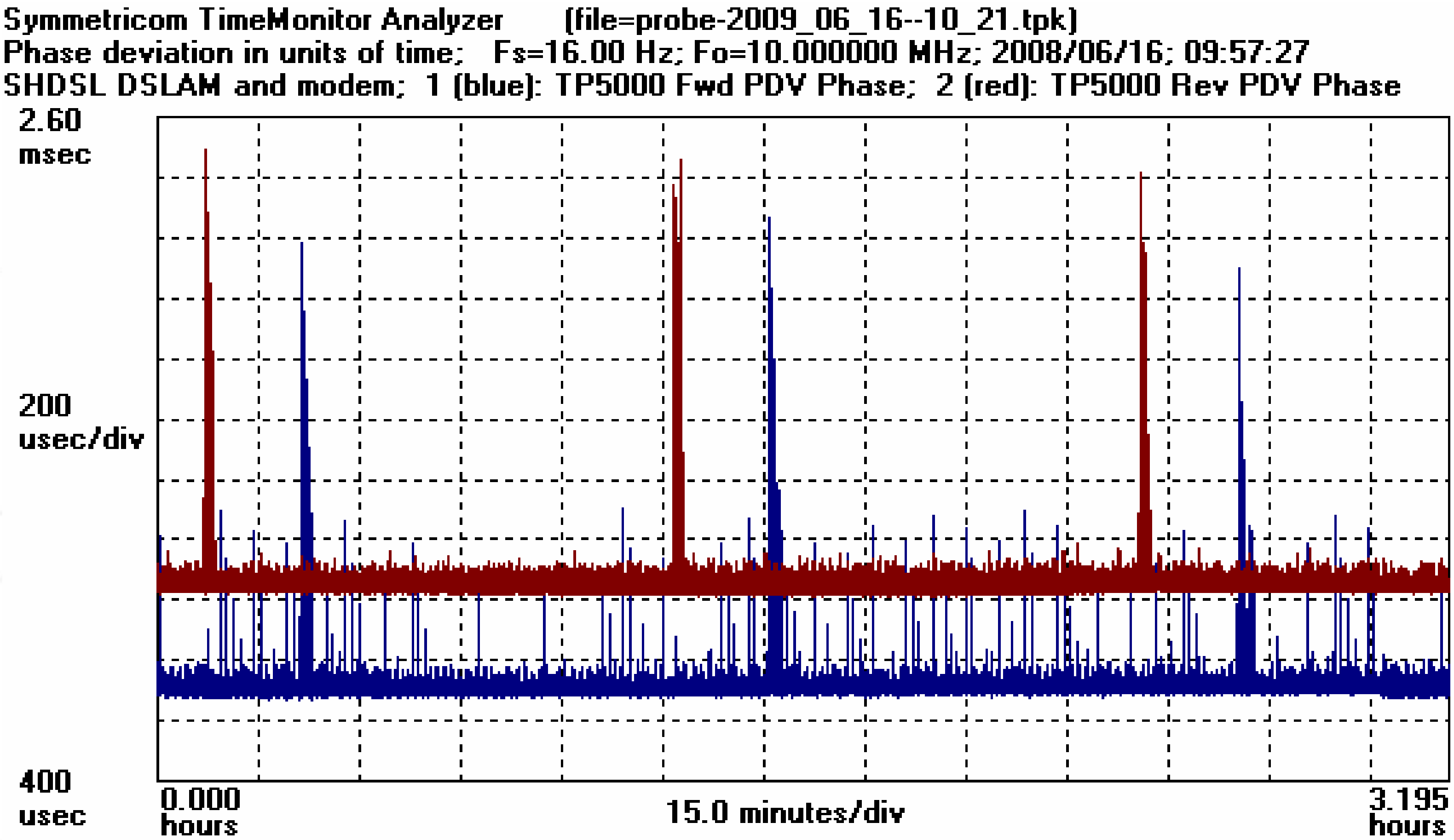
(Ethernet microwave radio packet delay pattern asymmetry)



Case Studies

Asymmetry in SHDSL

(SHDSL forward/reverse packet delay asymmetry)



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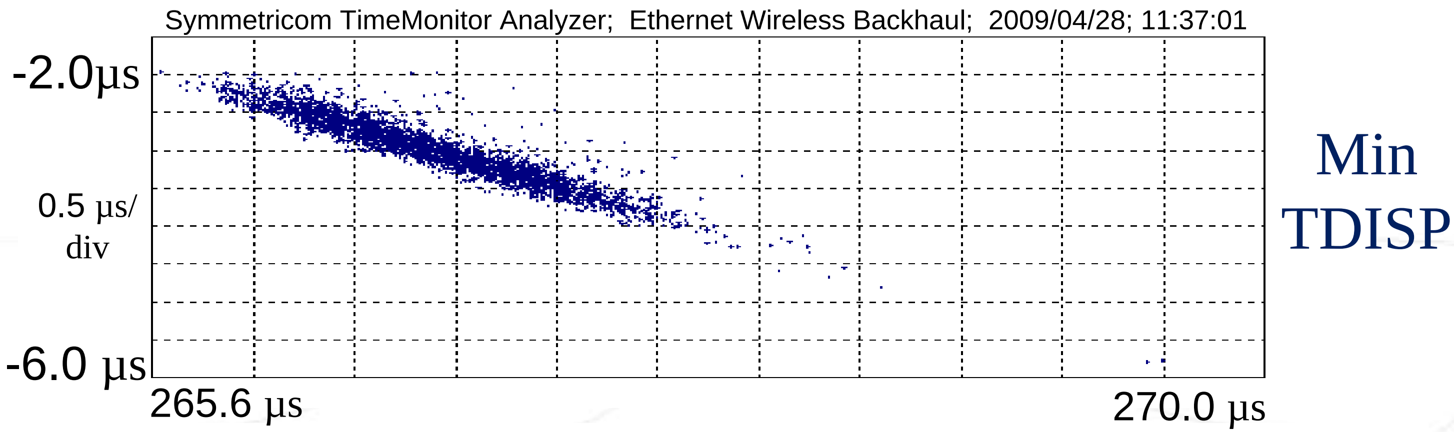
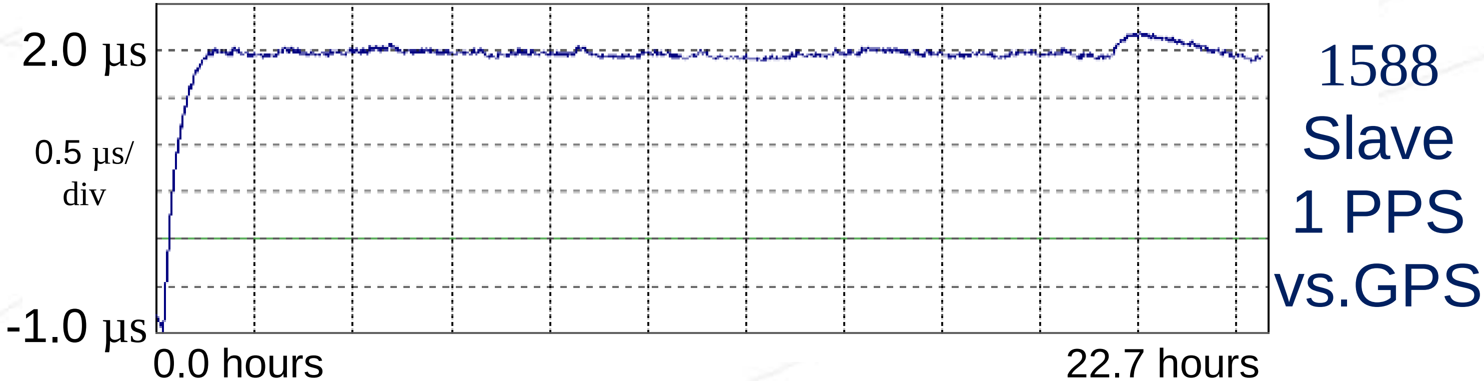
Asymmetry in Wireless Backhaul

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





Case Studies

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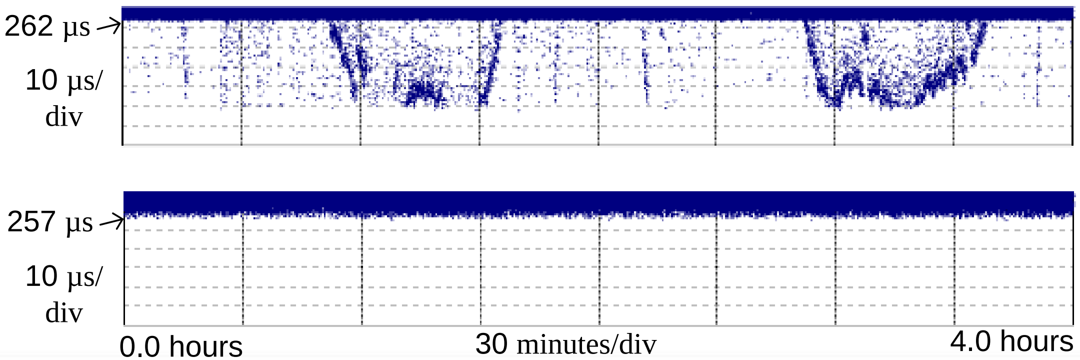
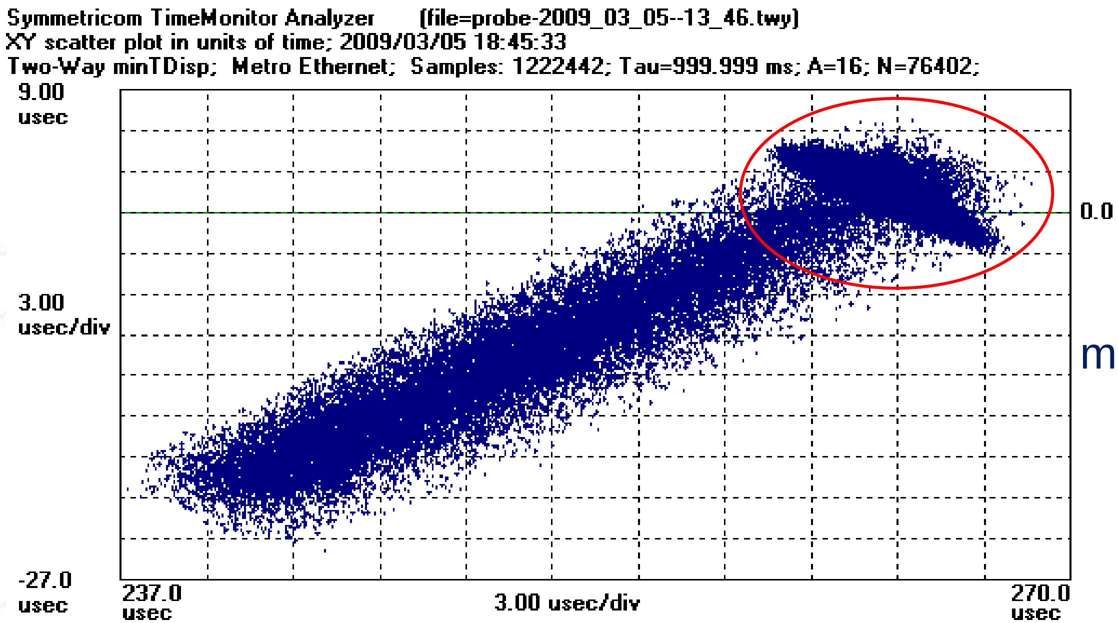
Metro Ethernet Network



Forward
PDV floor

Reverse
PDV floor

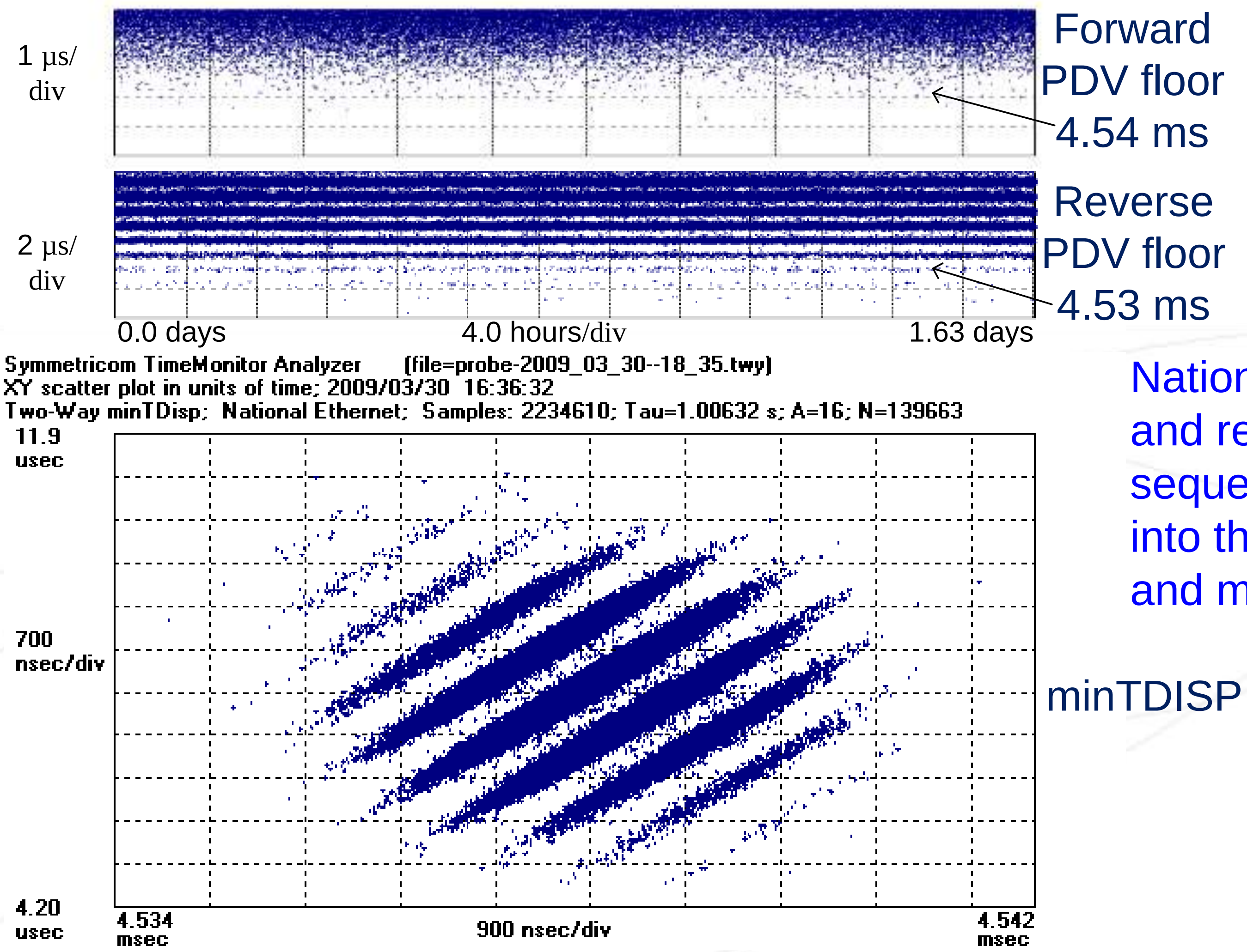


Metro Ethernet forward and reverse packet delay sequences with zooms into the respective floors and minTDISP

minTDISP

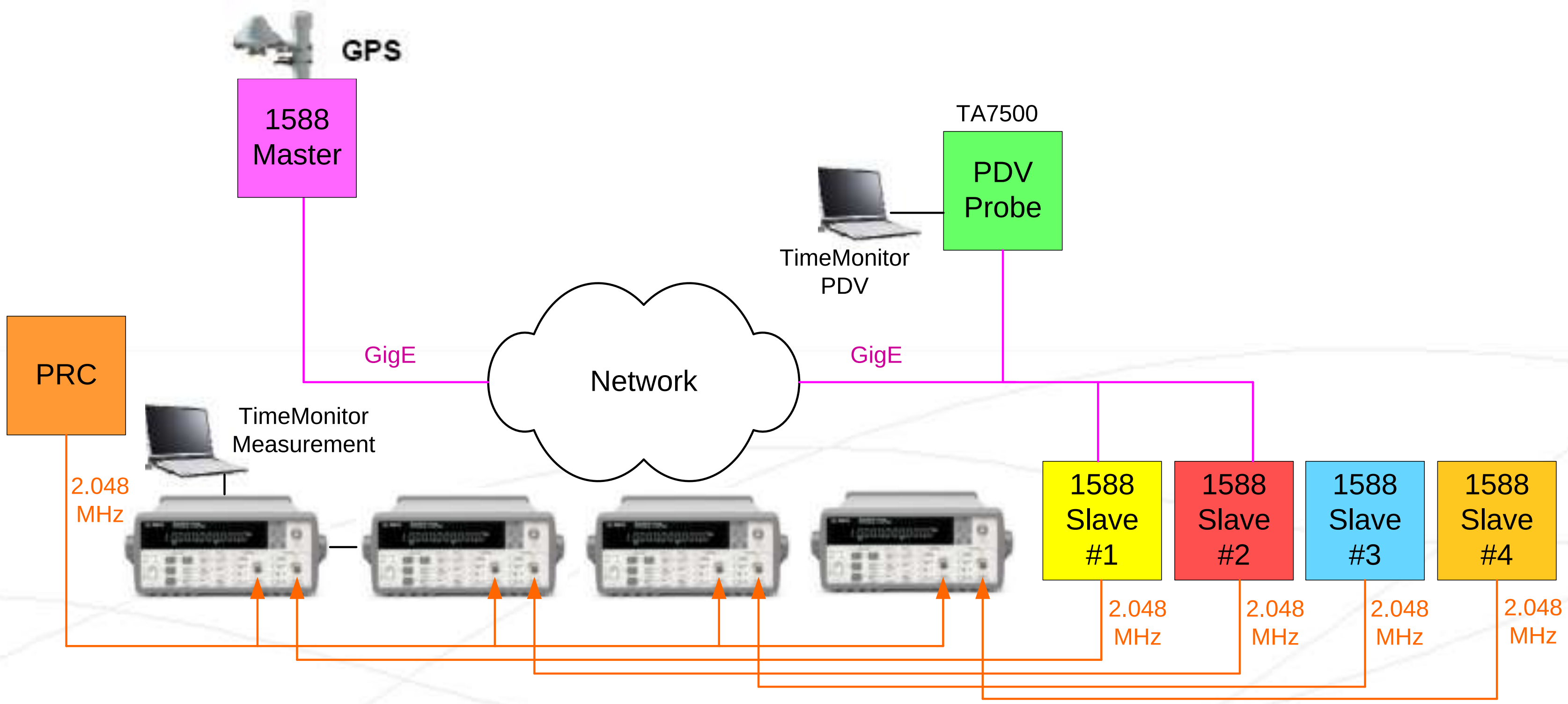
Case Studies

National Ethernet Network



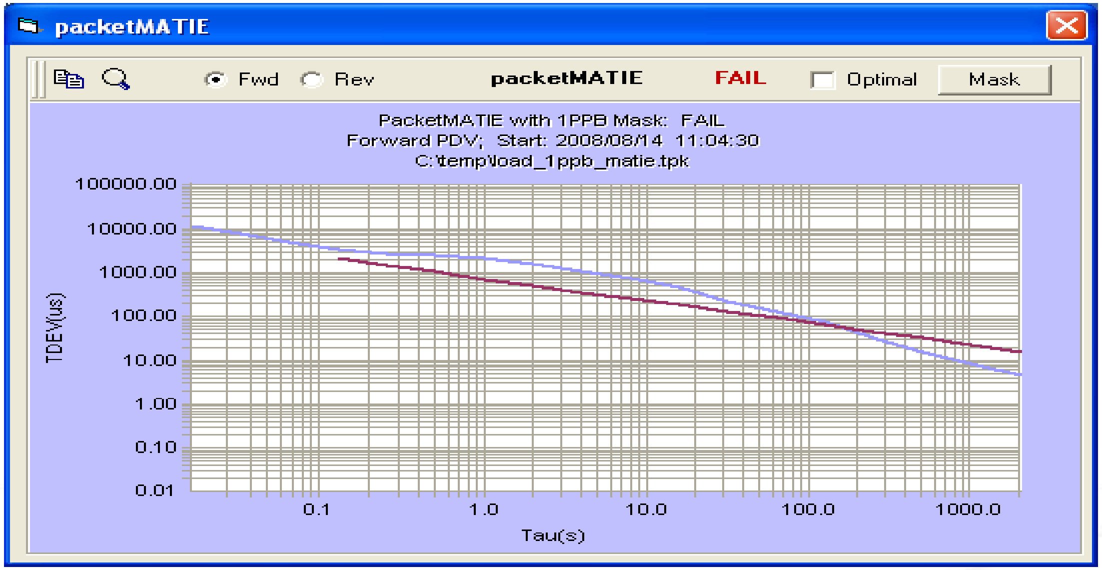
National Ethernet forward and reverse packet delay sequences with zooms into the respective floors and minTDISP

Sync in a Packet Network



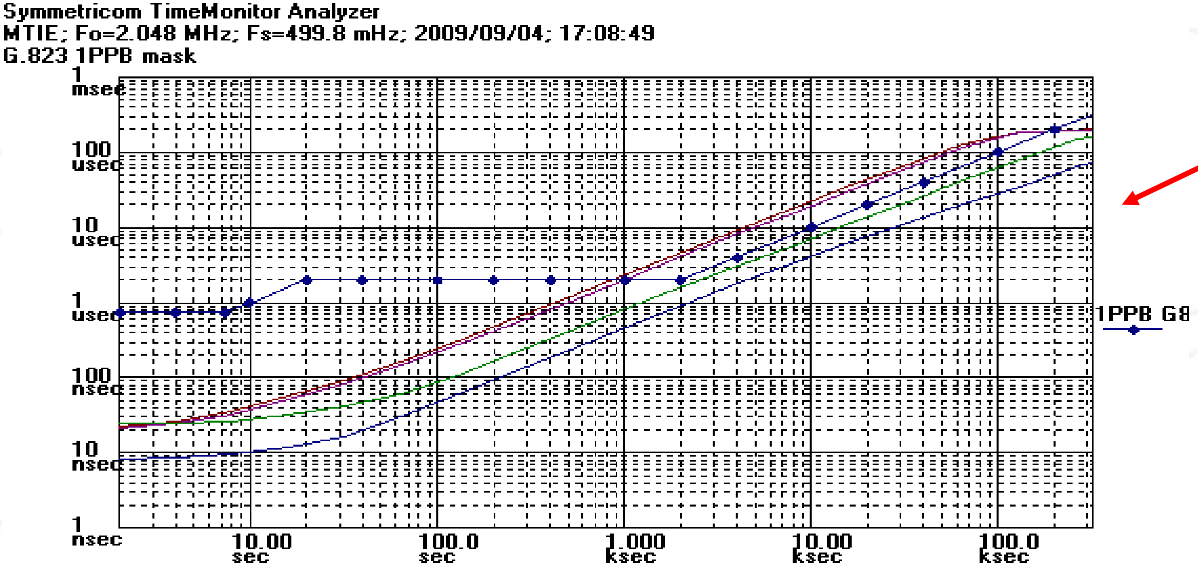
Measurement setup for measuring PDV and the outputs of four 1588 slaves

Sync in a Packet Network



Packet measurement

Packet data analysis:
1PPB offset predicted



Sync measurement

1588 slave performance:
1 PPB offset measured

PDV Metrics Accurately Predict IEEE 1588 Slave Performance

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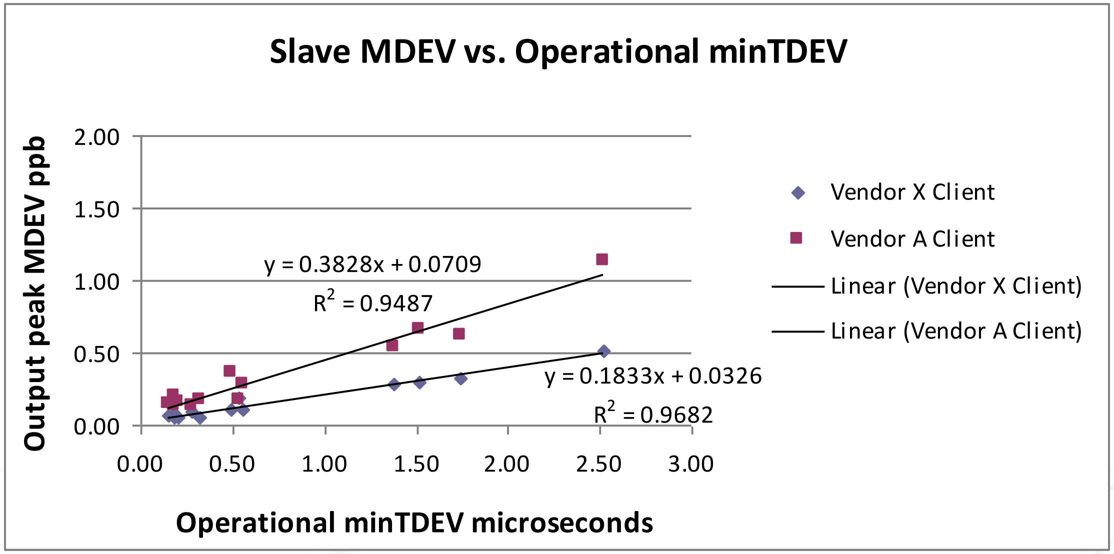
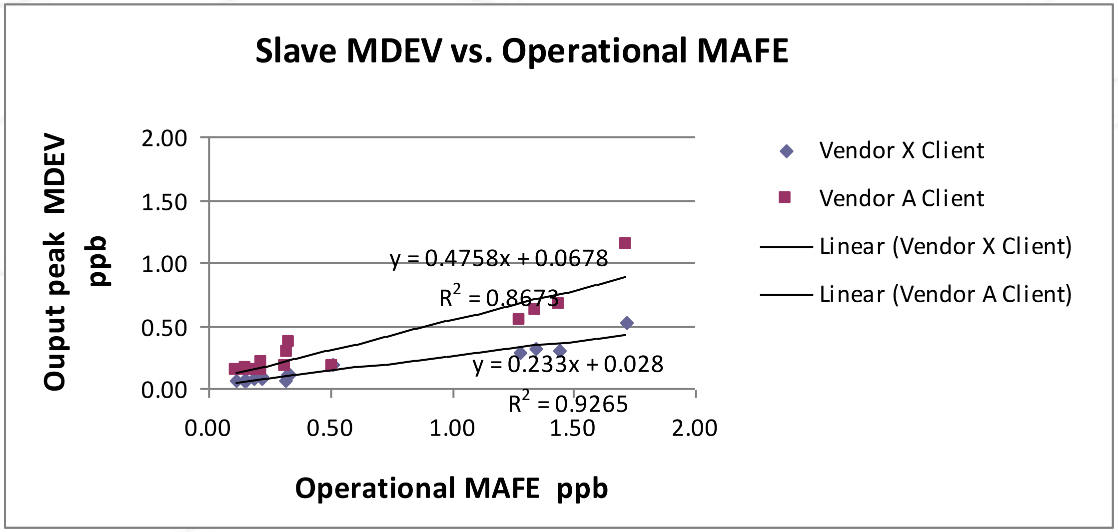
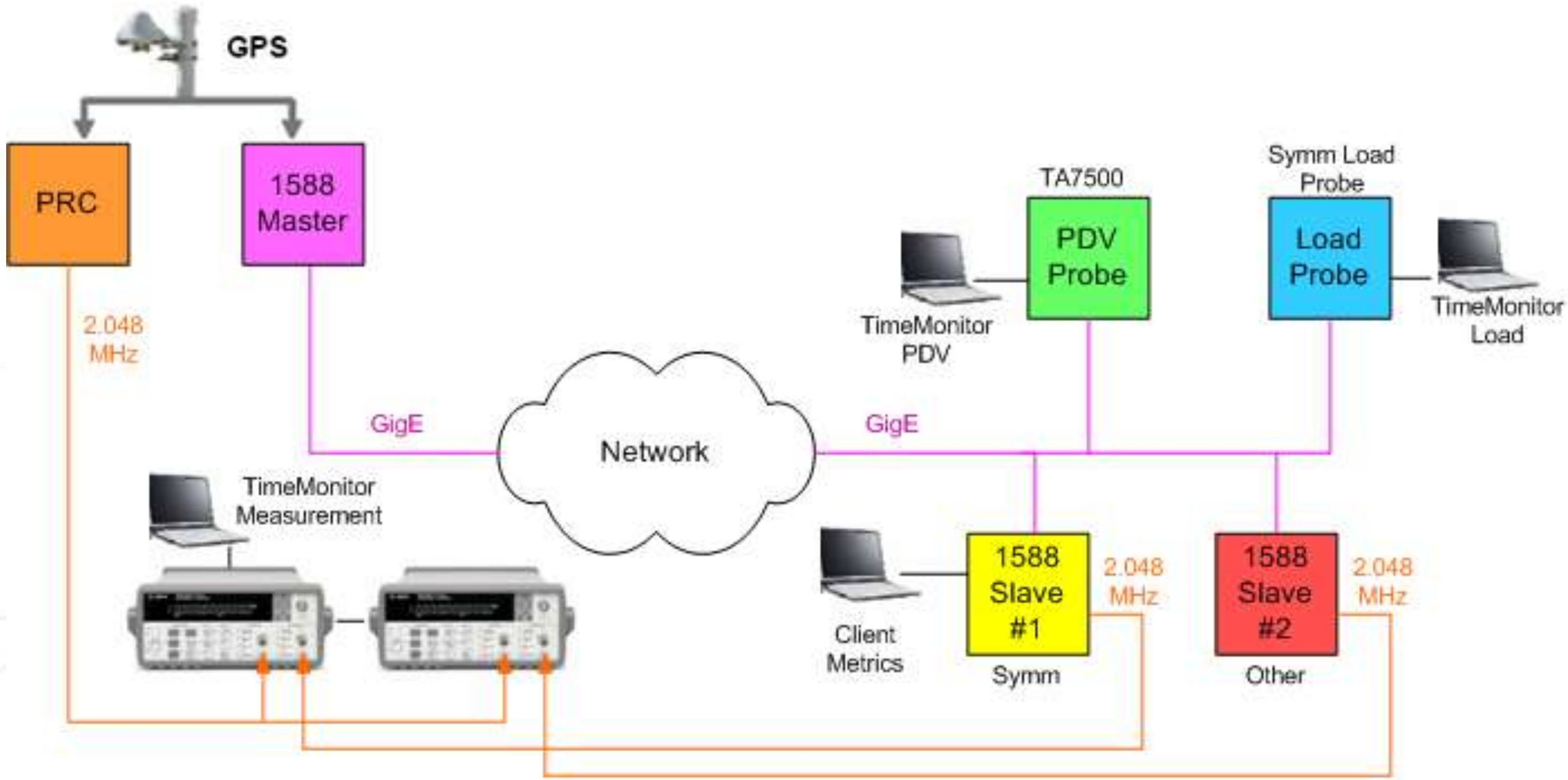
- ➢Operational Min_TDEV predicts frequency stability with >90% correlation for both clients
- ➢Operational MAFE achieves essentially the same level (>86%)
- ➢Slope of linear fit is a good measurement of static noise immunity (low is better)
  - ➢(Vendor X slope: 0.18, Vendor A slope: 0.38) (Operational Min_TDEV)
  - ➢ (Vendor X slope: 0.23, Vendor A slope: 0.47) (Operational MAFE)





"Load" Measurement Probe

Symmetricom

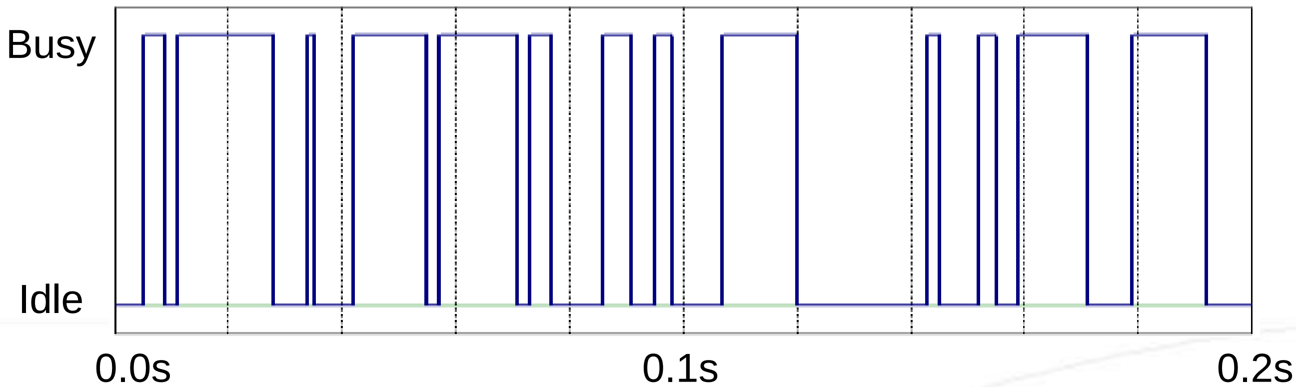


Measurement setup for measuring (1) Sync, (2) PDV, and (3) Load

Packet Load Probe

Symmetricom

Instantaneous packet flow and the derivation of dynamic packet load parameters



Packet Load

(200 msec)

Packets		312		1523		95		1167		1030		290		365		297			1245		151		175		1091		1207	
Busy (ms)		4		17		1		13		14		4		5		3			13		2		3		12		13	
Idle (ms)	5		2		6		7		2		2		9		4		2	7		23		7		4		8		8

Sample #1 — Sample #2

	Packets	Idle	Min Idle	Max Idle	Busy	Min Busy	Max Busy
Sample #1	5079	39%	2ms	9ms	61%	1ms	17ms
Sample #2	3869	57%	4ms	23ms	43%	2ms	13ms

Packet Load Probe

Symmetricom

Fast FPGA hardware provides real-time packet statistics on all packets: average/minimum/maximum busy and idle times for each sample.

Timestamp

Different packet streams

*:008A7484.320859192:AA84008B
0:62123:24617187:75:1525:37883420:11:1584
1:62123:24617187:75:1525:37883420:11:1584
3:62123:24617187:75:1525:37883420:11:1584
7:62125:24617412:75:1525:37883195:11:1584

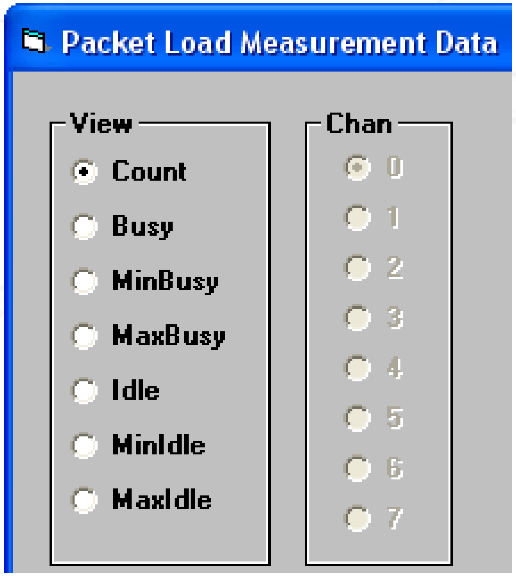
Sample #1

*:008A7484.820859192:AA85008F
0:59087:12097908:76:588:50402208:132:1590
1:59087:12097908:76:588:50402208:132:1590
2:1:98:98:98:124999904:124999904:124999904
3:59087:12097908:76:588:50402208:132:1590
7:59089:12098123:76:588:50401993:132:1590

Sample #2

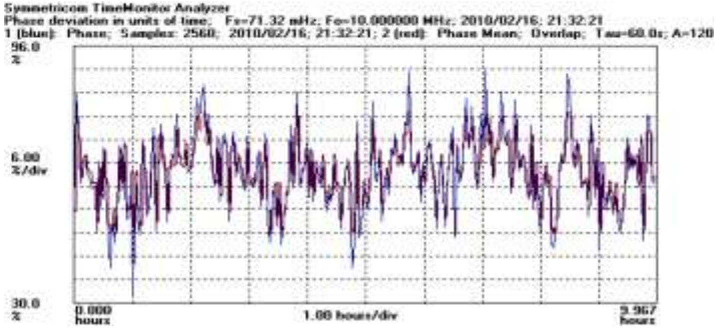
Count/Busy/MinBusy/MaxBusy/Idle/MinIdle/MaxIdle

Example packet streams:
PTP, NTP, VLAN, All



Traffic Generator Input vs. Load

Check of initial packet load prototype: it works – measured load matches traffic generator sequence



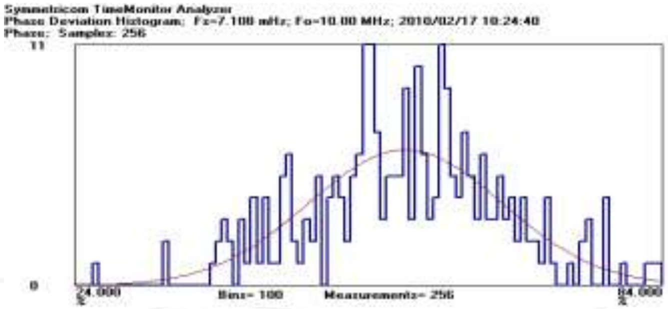
Dynamic load over time

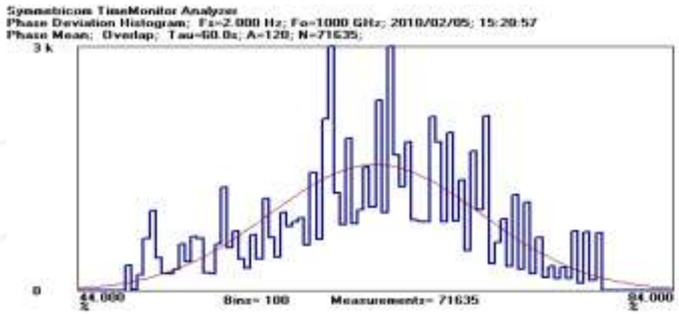
(Left: 10 hours

Right: Zoom)

(Blue: Traffic generator

Red: Load probe)

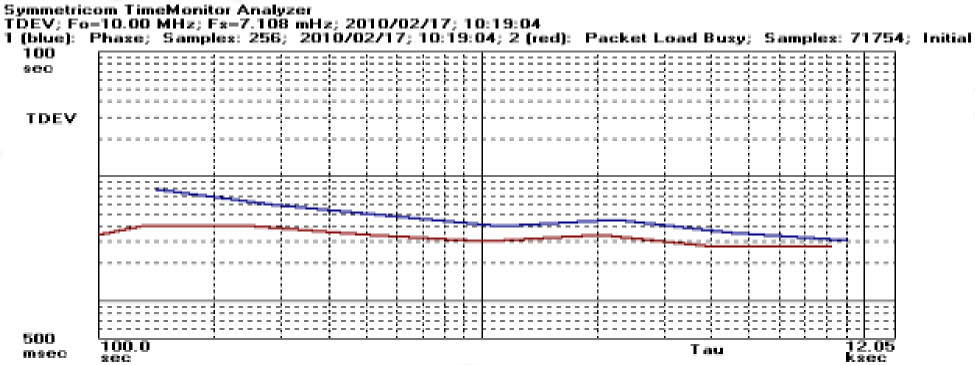




Histogram/Statistics

(Left: Traffic generator

Right: Load probe)

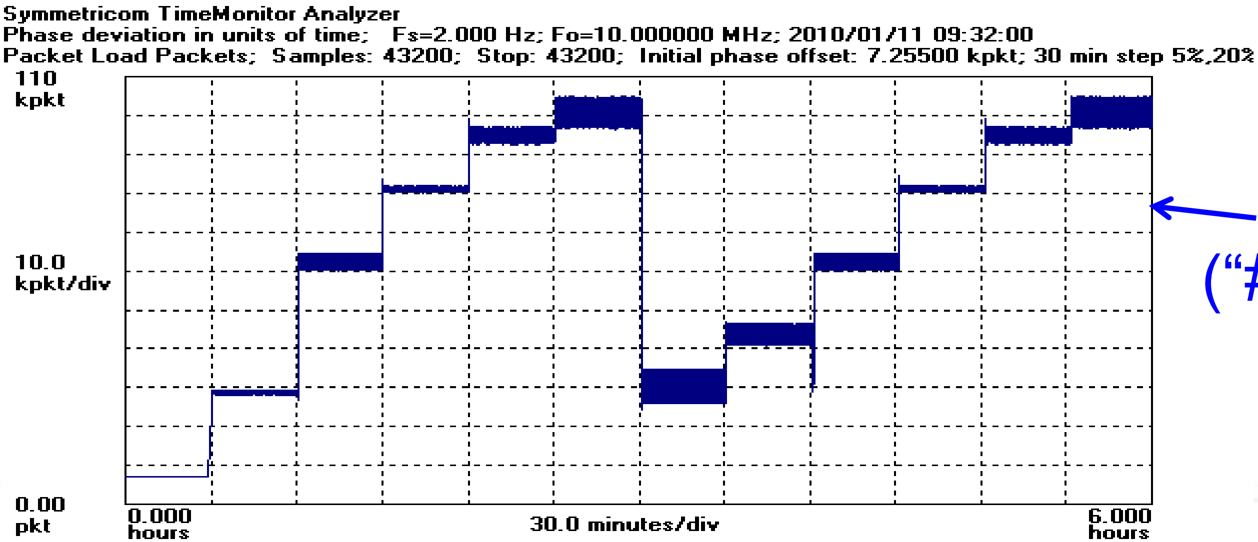


TDEV Analysis

(Blue: Traffic generator

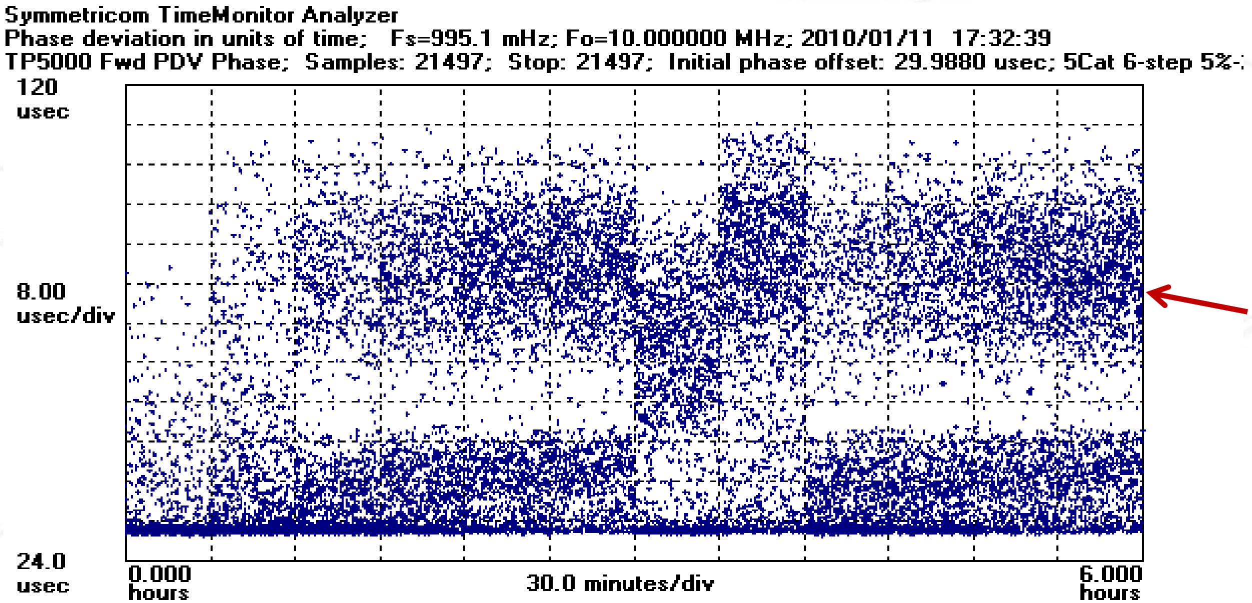
Red: Load probe)

“Load” and “PDV” Compared



Measured load

(“# packets/sample”)



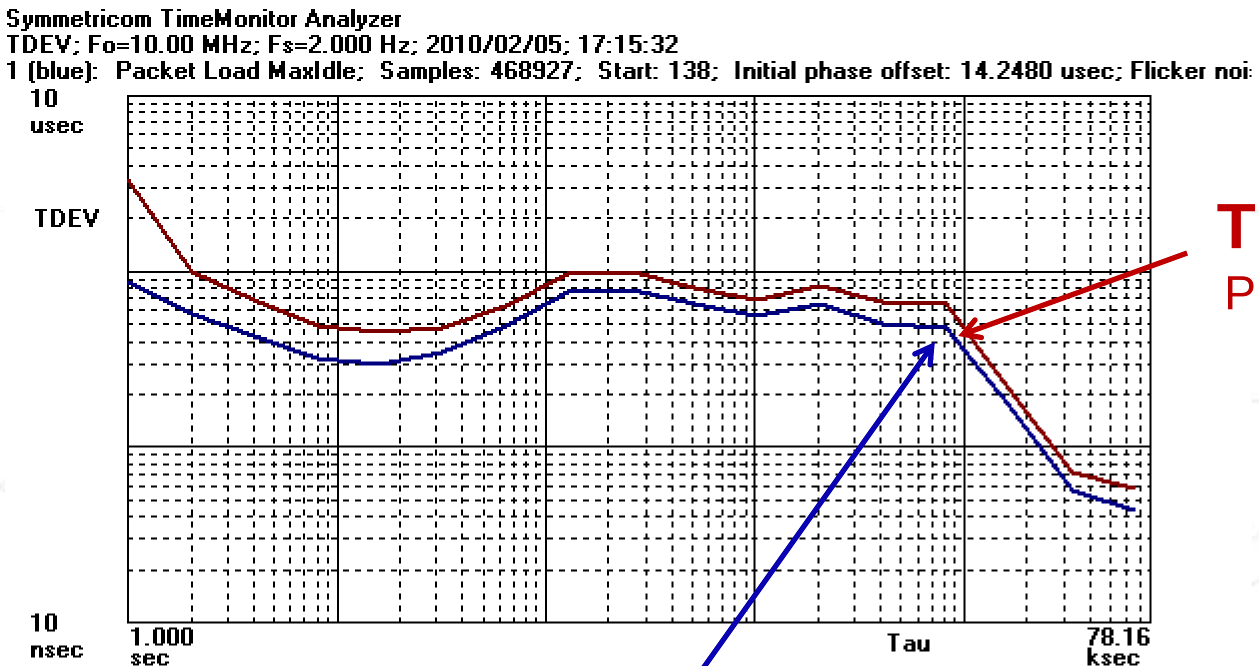
Measured PDV

Dynamic Load and PDV

There is a strong relationship between load and PDV

(1) A load probe could be used to show aspects of PDV behavior

(2) Conversely, PDV measurements show load characteristics directly



TP5000 probe

PDV measurement

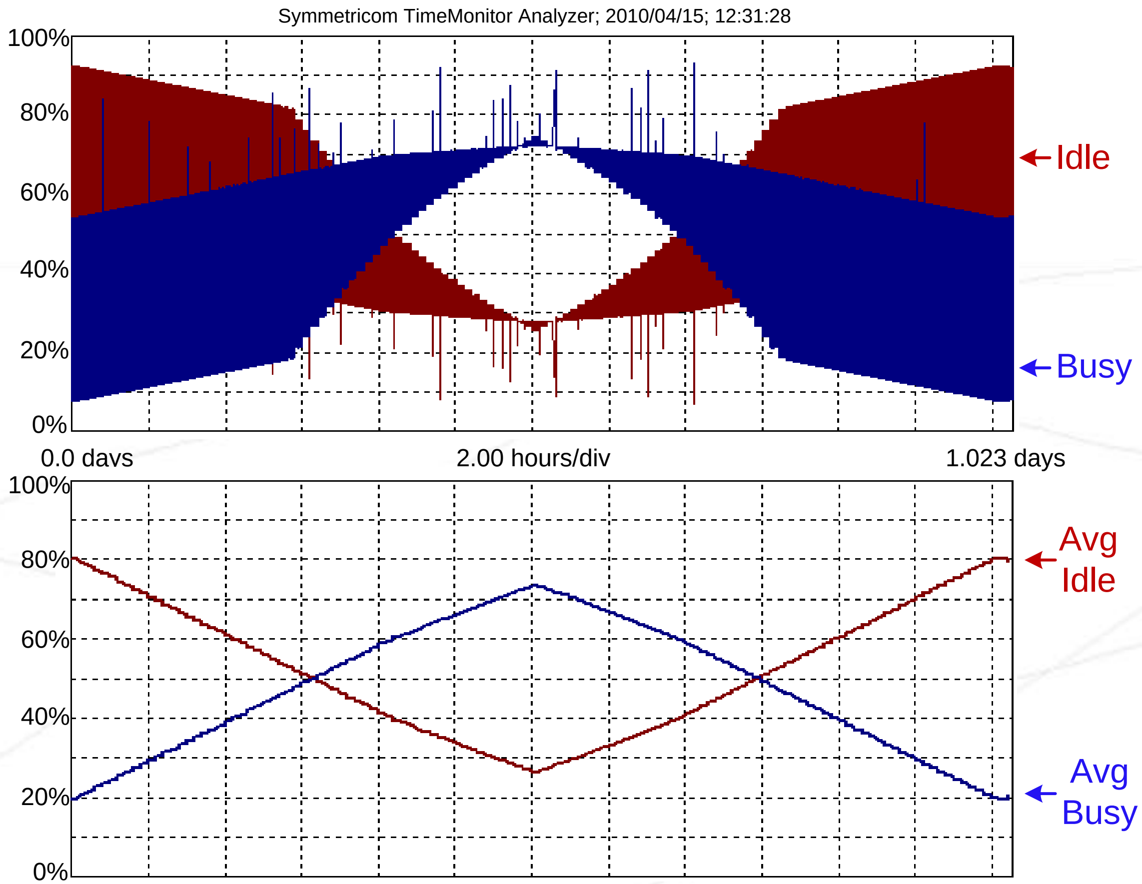
Load probe

Measured load “max idle”

Traffic Generator Characterization

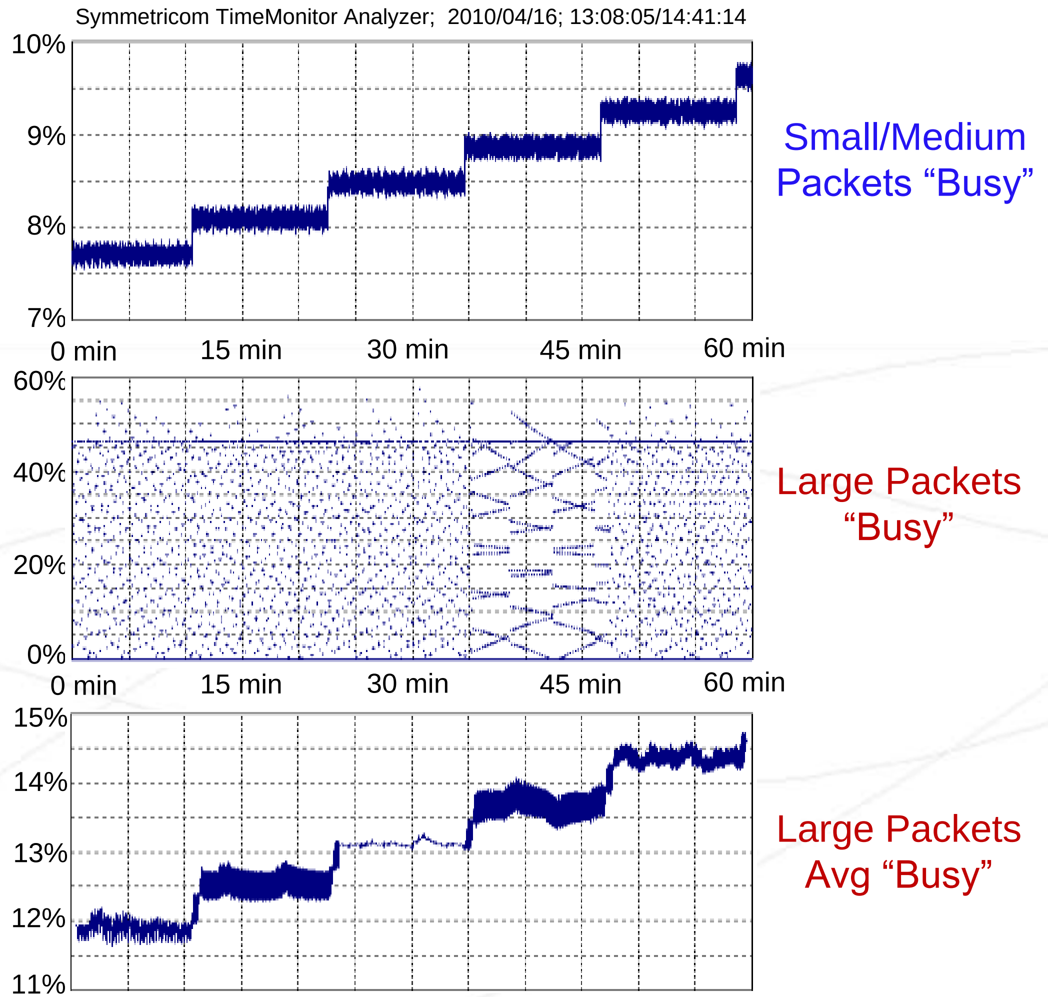
Symmetricom

Traffic generator load for 24 hour ramp 20% to 80% from combined small/medium and large packet streams with 0.5 second samples in the upper plot and 60 second averages in the lower plot



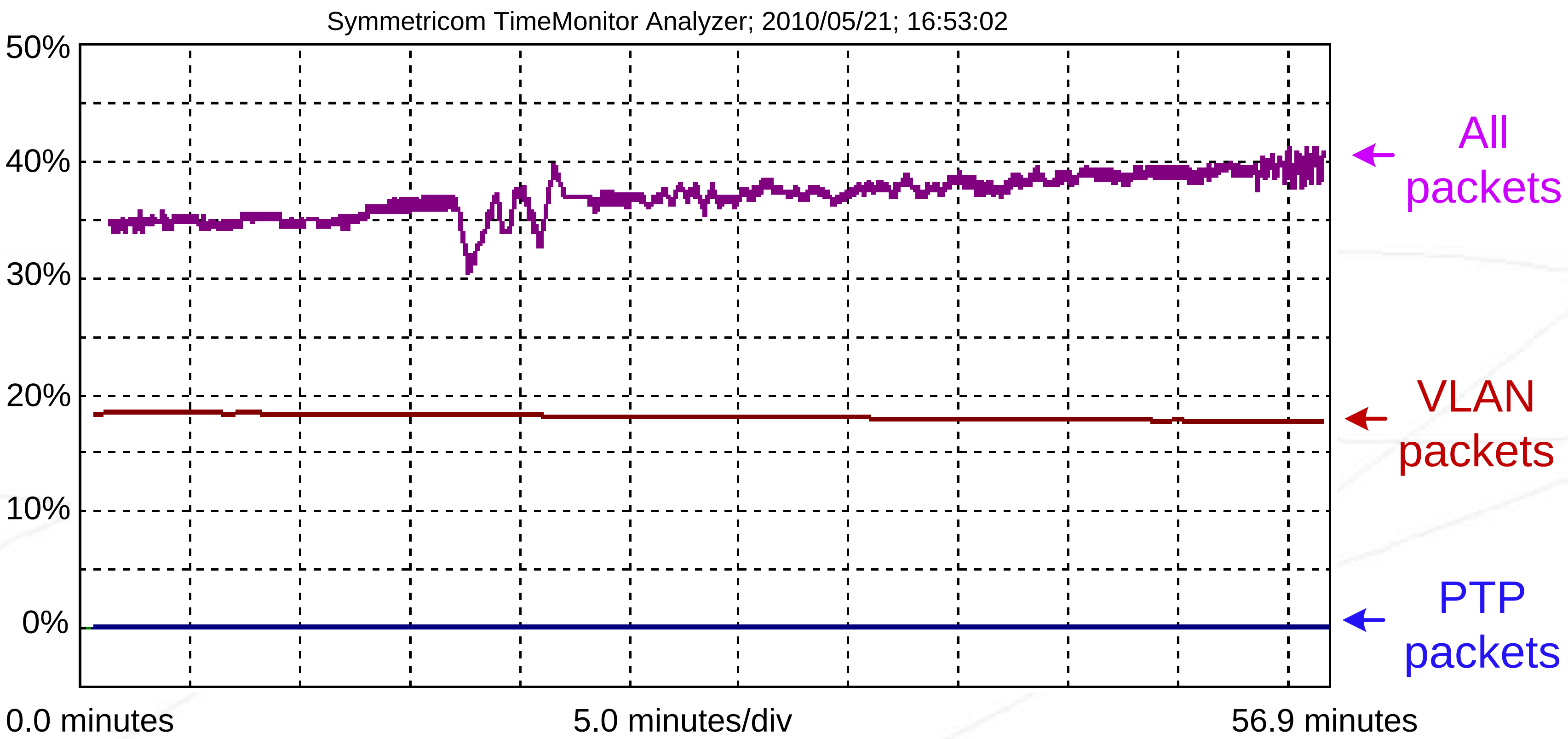
Traffic Generator Characterization

The traffic generator was setup with two streams, small/medium size packets with uniform load and large packets with bursts. Measurements with the load probe reveal this.



Multiple traffic streams

Here the load probe is simultaneously characterizing PTP packets, the packets in a particular VLAN, and the total packet stream



Summary

Symmetricom

- Three types of measurements discussed
  1. “TIE”
  2. Packet “PDV”
  3. Packet “Load”
- 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 measurement analysis can be used to predict packet slave performance
- Load Probe
  - Third measurement type
  - Primary reference clock not required
  - “Load” and “PDV” are related

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