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# Tutorial on Measurements and Metrics for Frequency, Time, and Packet Signals

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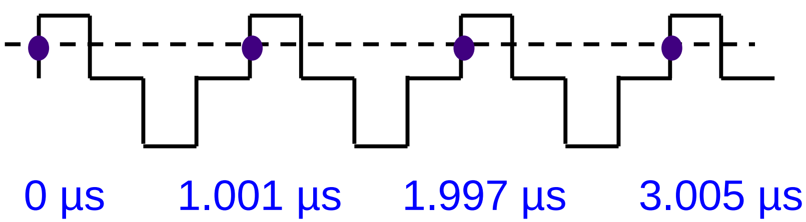
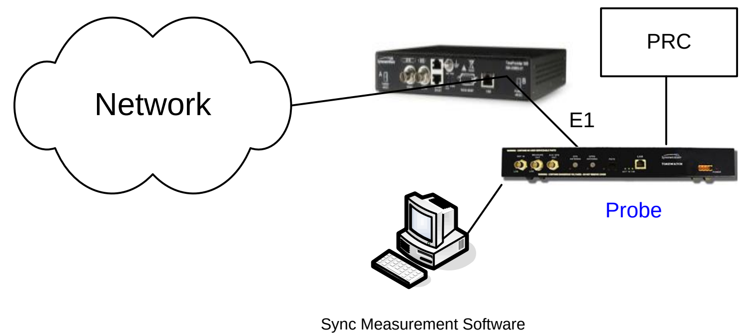
# Presentation Outline

- 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
    - Five networks: PDV
    - Backhaul network: time transport
- Conclusions

# Frequency signal “TIE” vs. “PDV”

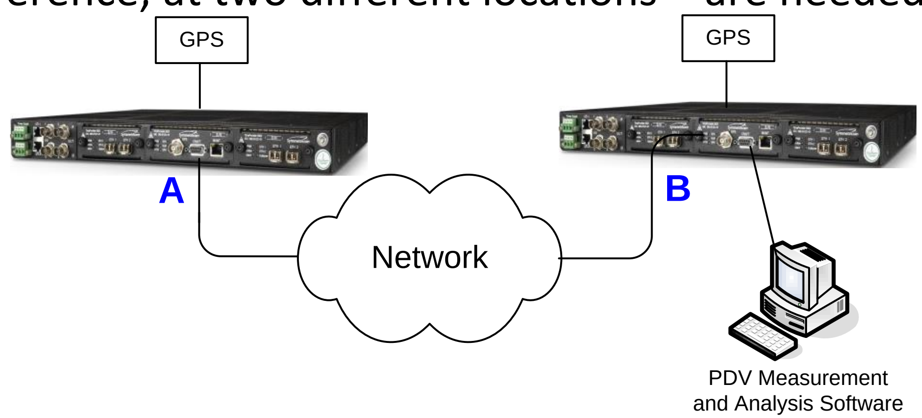
- “TIE” (Single Point Measurement)
  – Measurements are made at a single point – a single piece of equipment in a single location - a phase detector with reference - is needed




- “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

| | 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 |



# Time signal “Physical” vs. “Packet”

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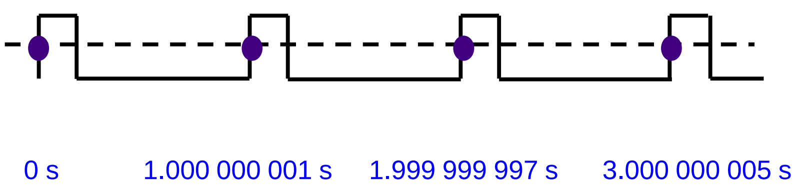
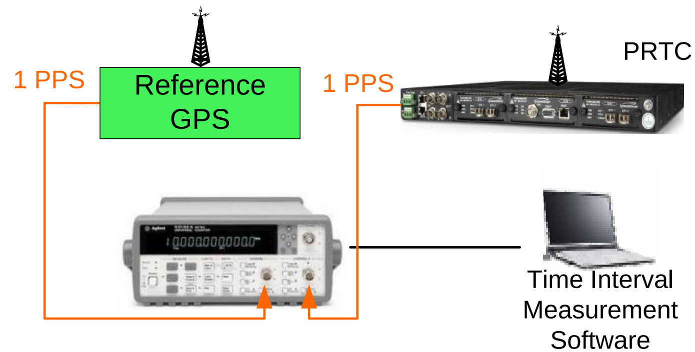
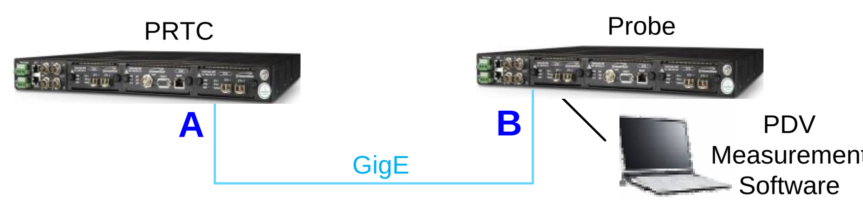
- “1 PPS” (Single Point Measurement)
  - Measurements are made at a single point – a single piece of equipment in a single location - a phase detector with reference - is needed



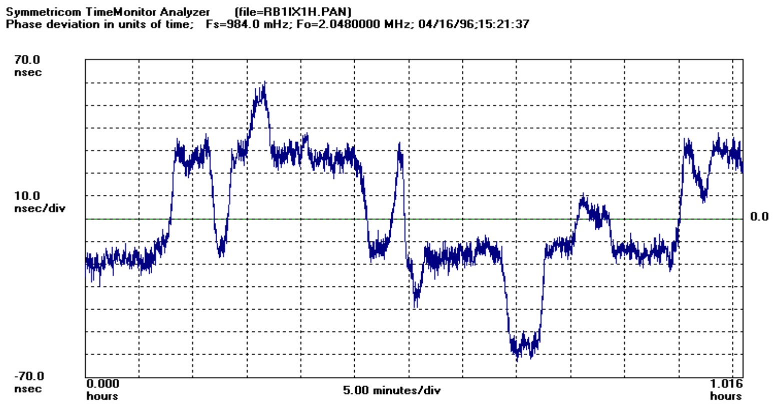




- “Packet” (Dual Point Measurement)
  - Measurements are constructed from packets time-stamped at two points – in general two pieces of equipment, each with a reference, at two different locations – are needed

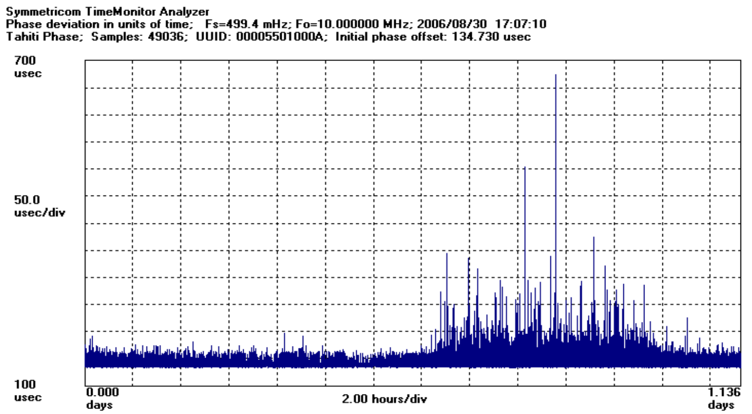
| | Timestamp A | Timestamp B |
|---|---|---|
| F | 1286231440.883338640 | 1286231440.883338796 |
| R | 1286231441.506929352 | 1286231441.506929500 |
| F | 1286231441.883338640 | 1286231441.883338796 |
| R | 1286231442.506929352 | 1286231442.506929500 |
| F | 1286231442.883338640 | 1286231442.883338796 |
| R | 1286231443.506929352 | 1286231443.506929516 |



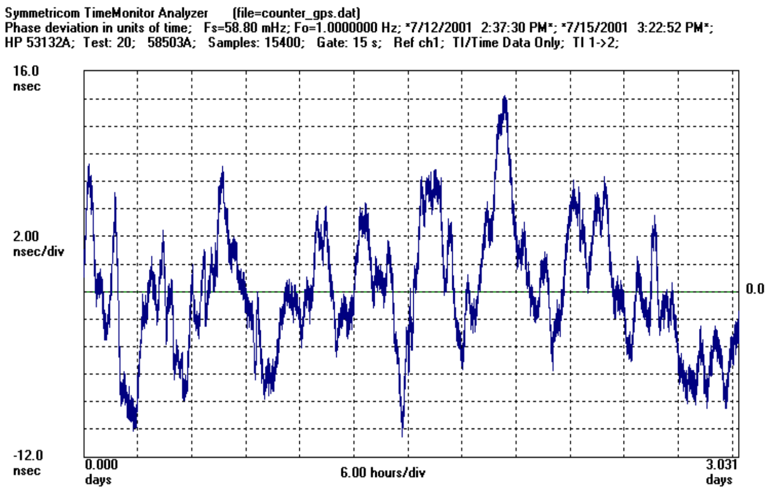
# TIE/PDV Measurements: Network vs. Equipment



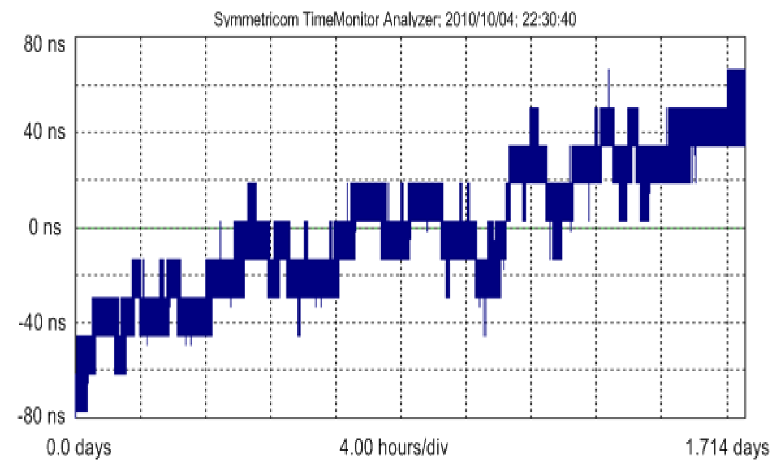

Network TIE




Network PDV




Equipment TIE




Equipment PDV

# Packet Probe

## Passive Probe vs. Active Probe

**Passive Probe**

(1) Hub or Ethernet Tap
(2) IEEE 1588 Slave
(3) Collection at Both Nodes

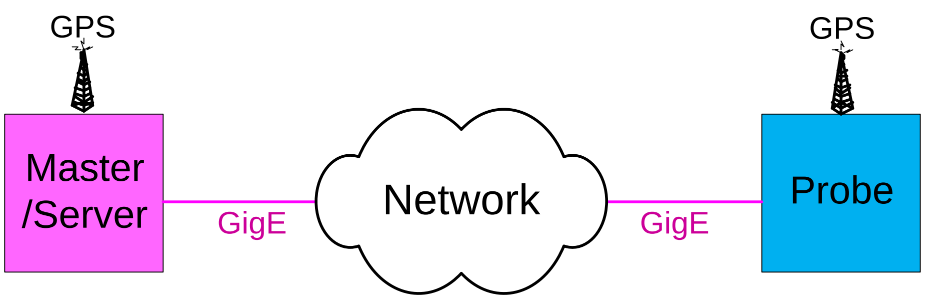
Passive probe sniffs packets: extra equipment required

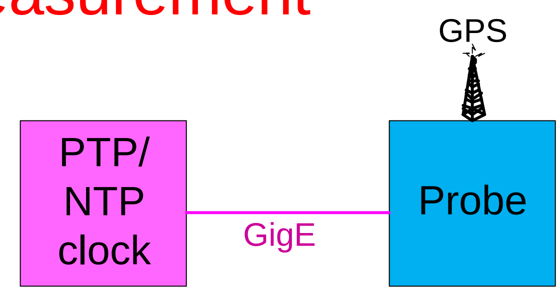
**Active Probe**

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

Active probe generates protocol: self-contained

## Network vs. Equipment PDV Measurement

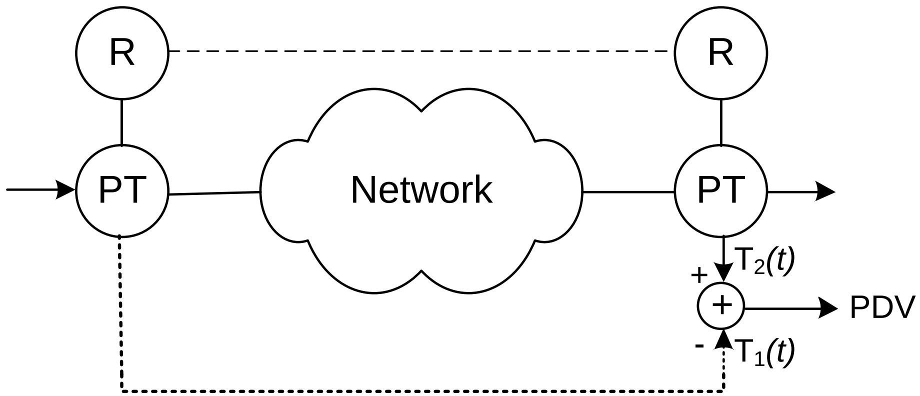



PTP GM/TC/BC
NTP server

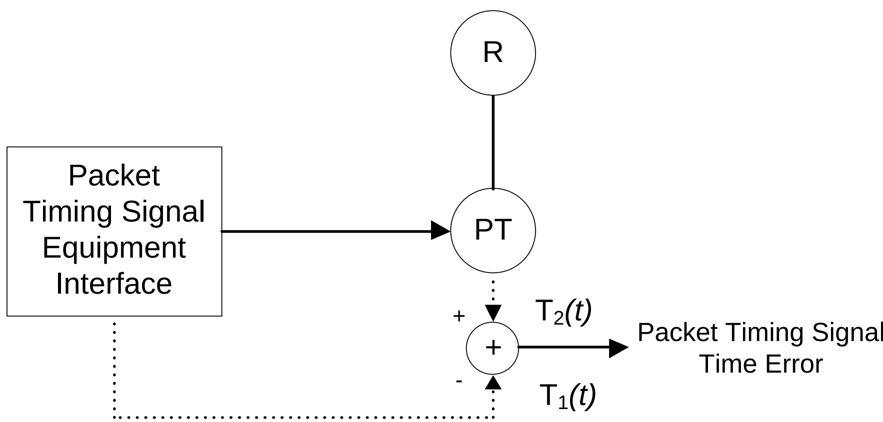
# Packet Probe (G.8260 View)

## Network PDV Measurement




| | |
|---|---|
| R | Time or frequency reference |
| PT | Packet timestamper |

## Packet Equipment Characterization




| | |
|---|---|
| R | Time or frequency reference |
| PT | Packet timestamper |

# “TIE” Analysis vs. “PDV” Analysis

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## “TIE” Analysis (G.810)

- Phase (TIE)
- Frequency accuracy
- Dynamic frequency
- MTIE
- TDEV

## “PDV” Analysis (G.8260)

- Phase (PDV)
- Histogram/PDF*,CDF**,statistics
- Dynamic statistics
- MATIE/MAFE
- TDEV/minTDEV/bandTDEV
- Two-way metrics: minOffset 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*

# Stability Metrics

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- Traditional Clock Metrics
  - ADEV, TDEV, MTIE
  - Traditionally applied to oscillators, synchronization interfaces
  - Also applied to lab packet equipment measurements

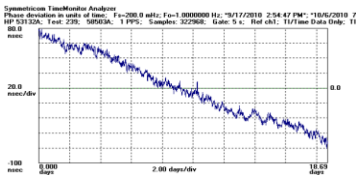
GM, BC

- Frequency Transport Packet Metrics
  - minTDEV, MAFE, MATIE
  - Applied to one-way packet delay data
  - FPP/FPR/FPC (floor packet percent/rate/count)

Packet Networks

- Time Transport Packet Metrics
  - minOffset or combine one-way (FPP, MAFE, etc.)
  - Applied to two-way packet delay data
  - Assesses link asymmetry

# Analysis from Phase: Frequency

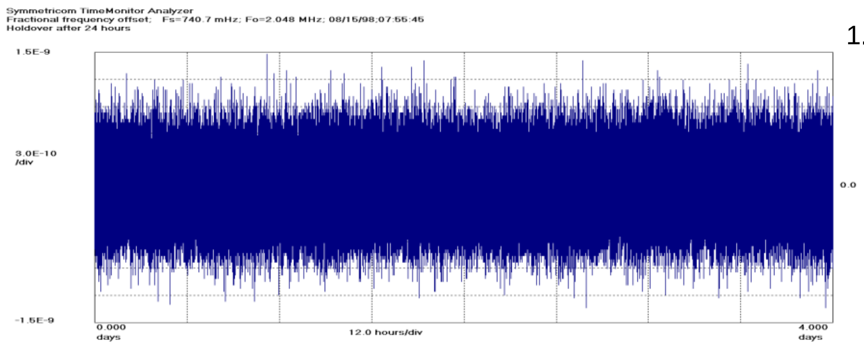



$-8.97 \cdot 10^{-14}$

## Frequency Accuracy

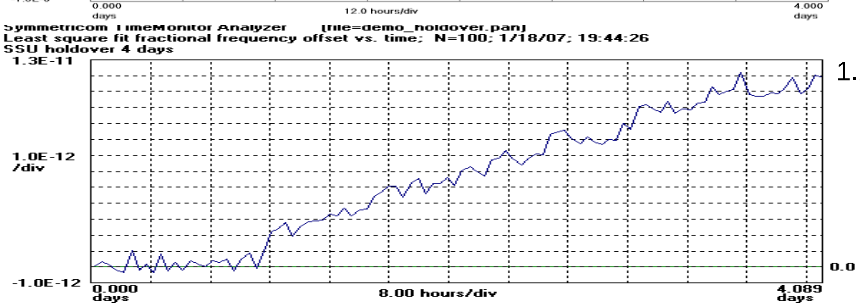
$$\omega = \frac{d\phi}{dt}$$

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



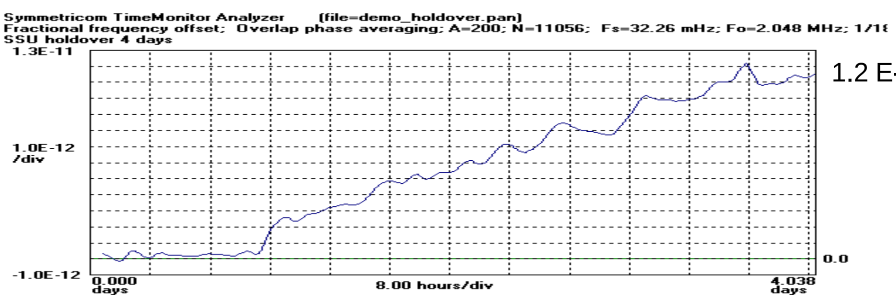

1.5 E-9

## Point-by-point




1.2 E-11

## Segmented LSF



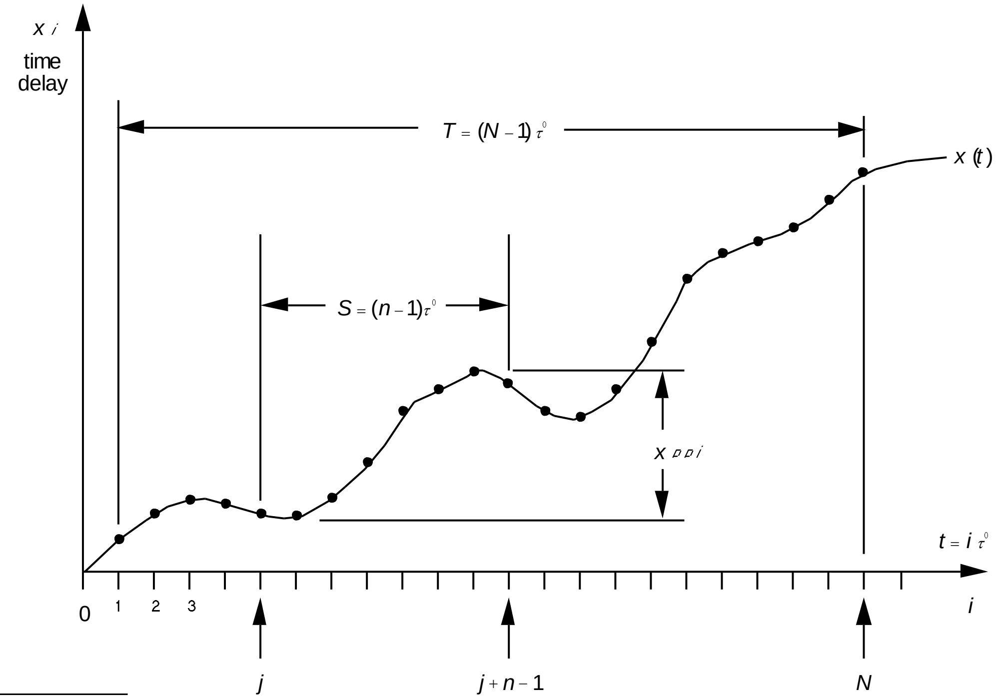

1.2 E-11

## 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

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

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

# Packet Selection Windows

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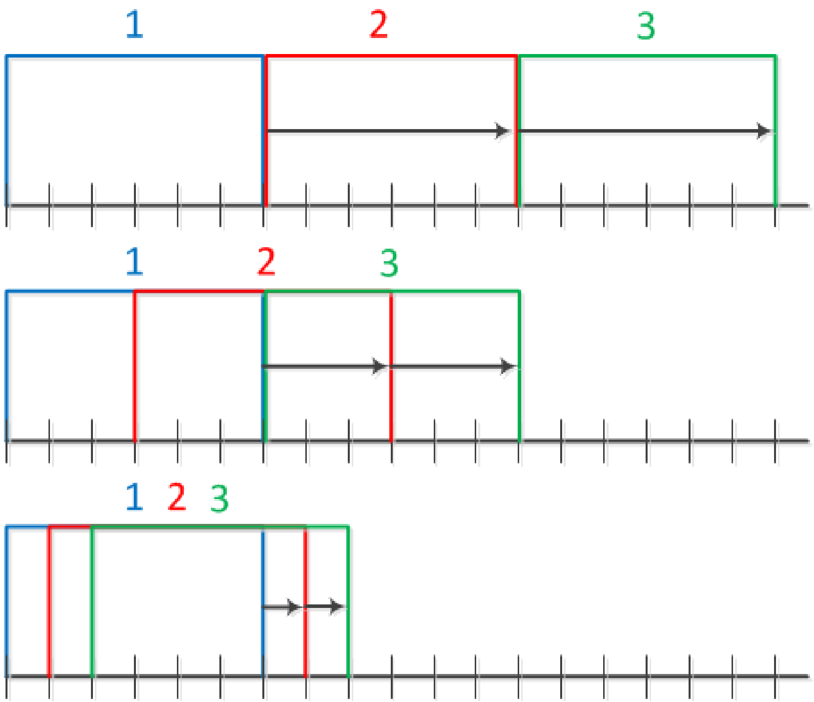
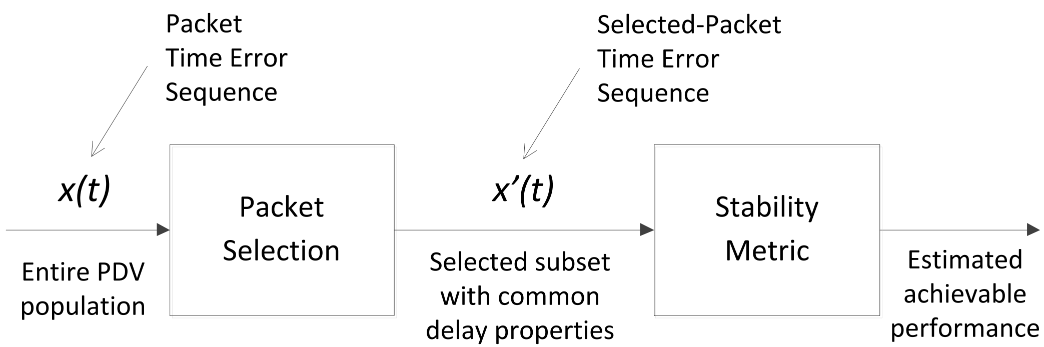
- Windows
  - ***Non-overlapping windows*** (next window starts at prior window stop)
  - ***Skip-overlapping windows*** (windows overlap but starting points skip over N samples)
  - ***Overlapping windows*** (windows slide sample by sample)

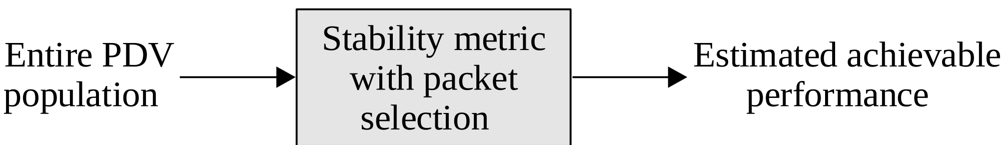



- Packet Selection Approaches (e.g. selecting fastest packets)
  - Select X% fastest packets (e.g. 2%)
  - Select N fastest packets (e.g. 10 fastest packets in a window)
  - Select all packets faster than Y (e.g. all packets faster than 150µs)

# G.8260 Appendix I Metrics

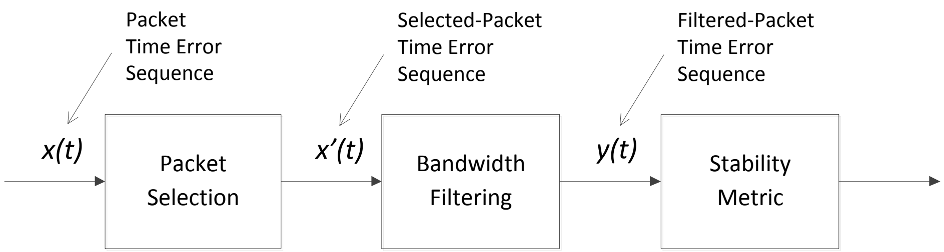



**Pre-processed packet selection**




G.8260(10)_FI.4

**Integrated packet selection**




**Metrics including pre-filtering**

FPC, FPR, FPP: Floor Packet Count/Rate/Percent

**PDV metrics studying minimum floor delay packet population**

# 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

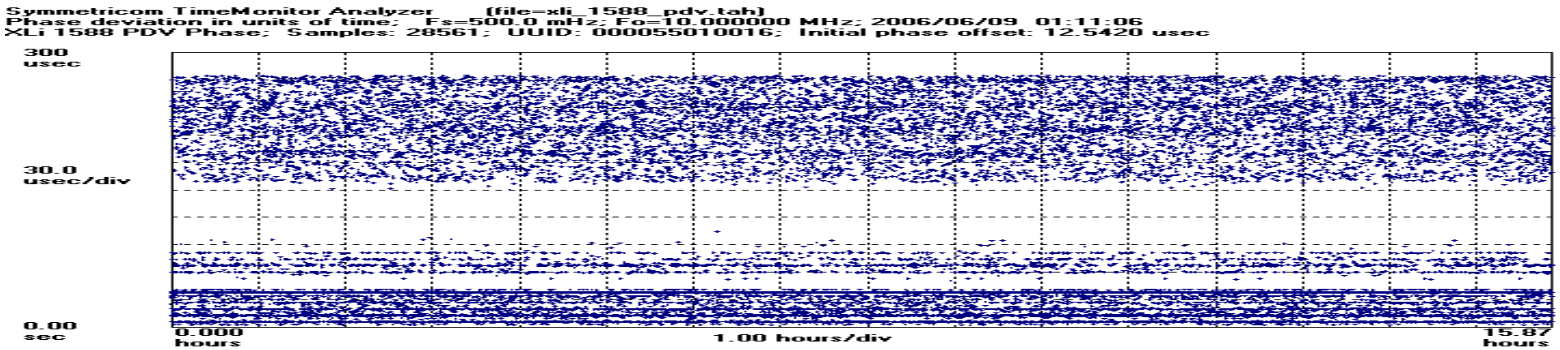
Forward

#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

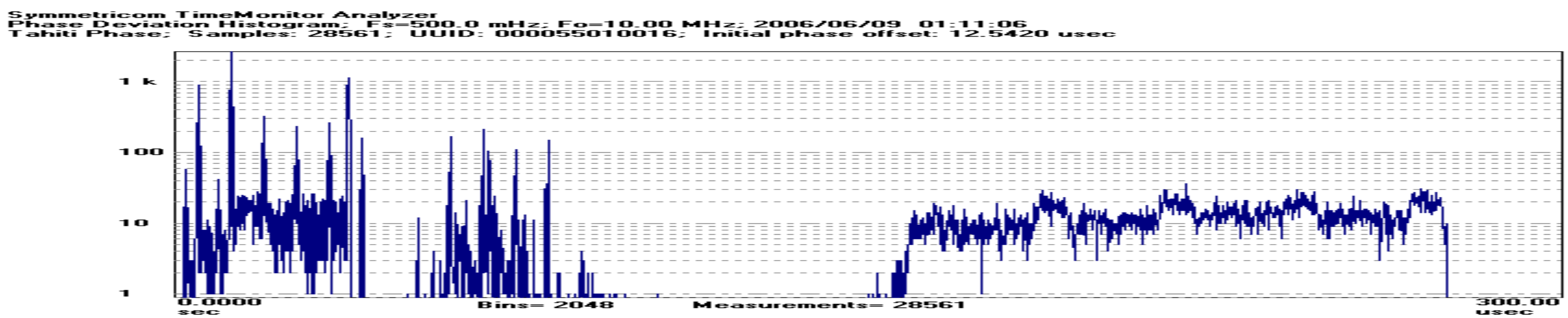
Reverse

#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



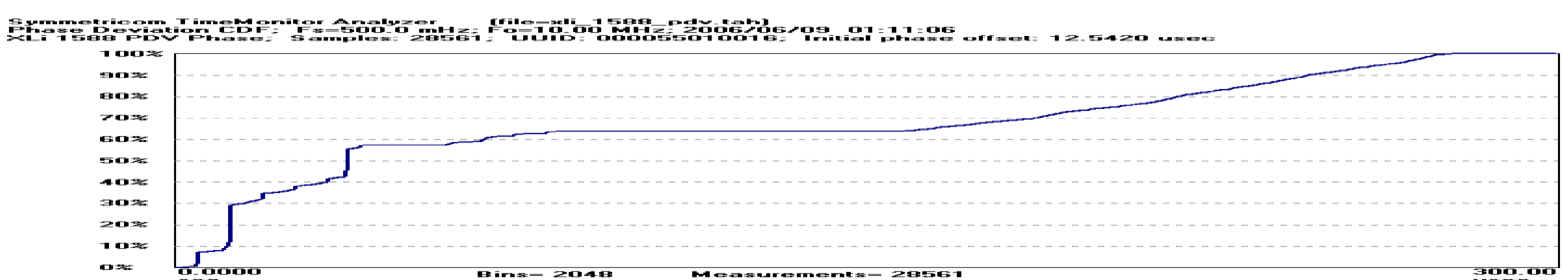

Packet Delay Sequence




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.%

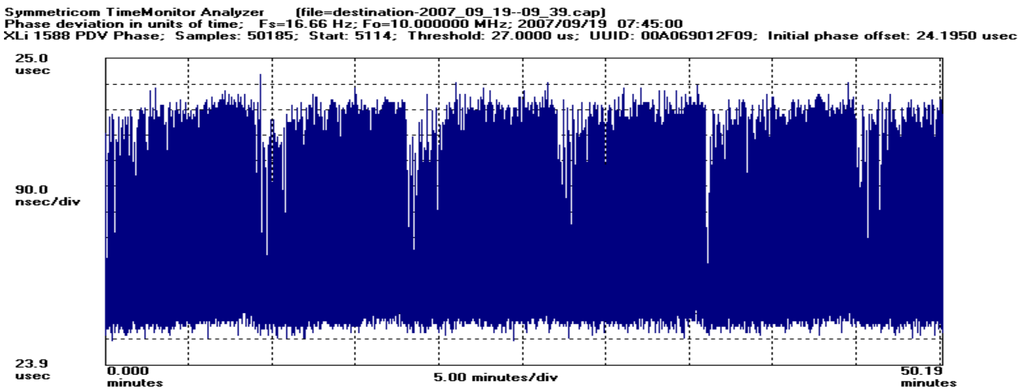
Statistics



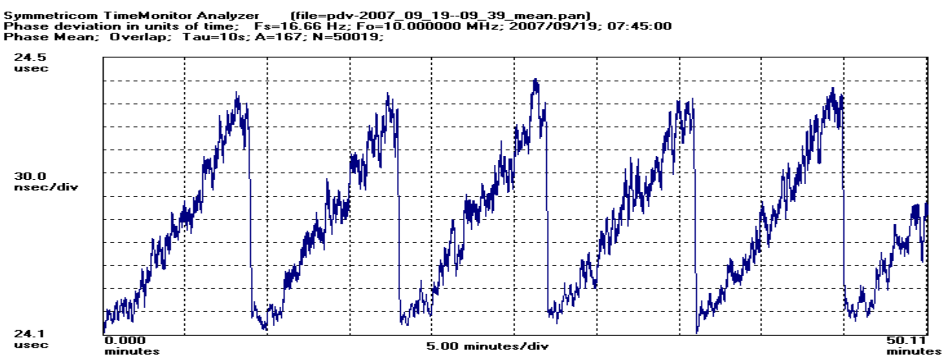

CDF

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

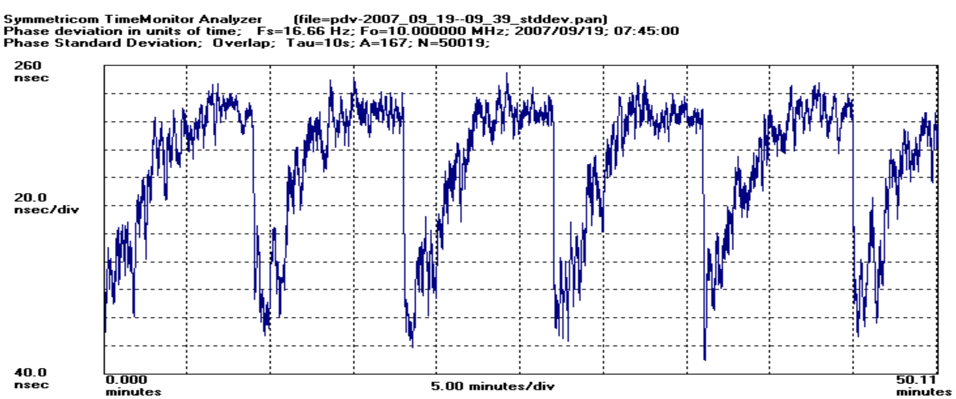
# Tracked Packet Delay Statistics




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

**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**

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

**bandTDEV**

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

PDV noise type characterization w/ packet selection

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**

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

**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

$$x_{\min}(i) = \min\left[x_j\right] for (i <= j <= i+n-1)$$

PDV frequency transport performance

**FPP**

$$FPP(n,W,\delta) = \left(\frac{\tau_P}{W}\right) \times FPC(n,W,\delta) \times 100\,\% \ \text{ for } (K-1) \le n < N$$

where

$$FPC(n,W,\delta) = \sum_{j=n-(K-1)}^{n} \phi_F(j,\delta) \ \text{ for } (K-1) \le n < N$$

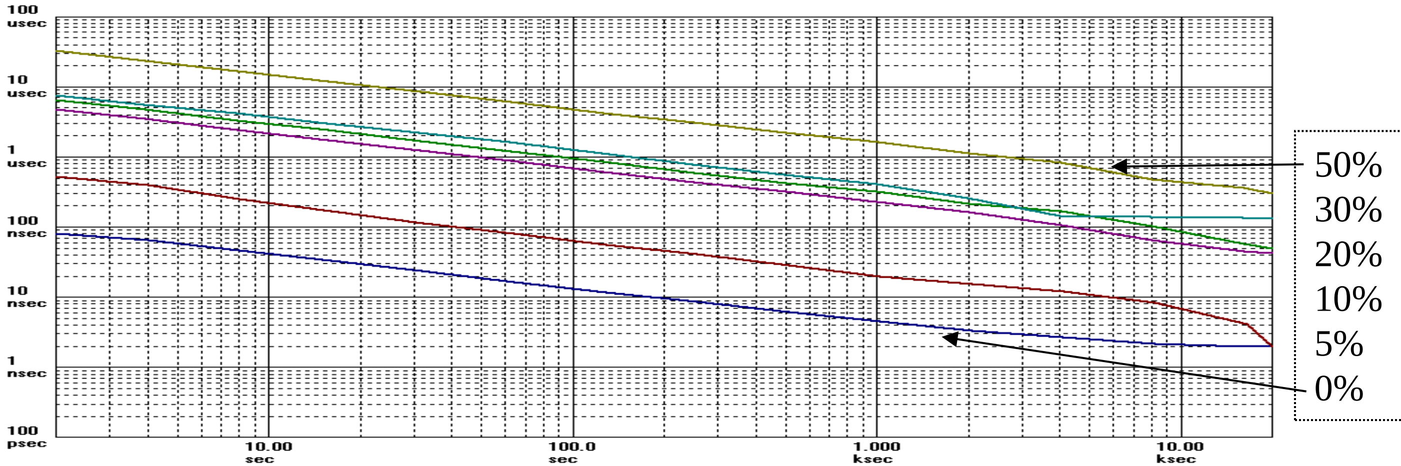
PDV phase/frequency delivery


References: (1) ITU-T G.8260 *Definitions and terminology for synchronization in packet networks*, Appendix I, Feb. 2012
(2) ATIS-0900003.2010 Technical Report: *Metrics Characterizing Packet-Based Network Synchronization*, Oct. 2010.

# TDEV & minTDEV with Traffic

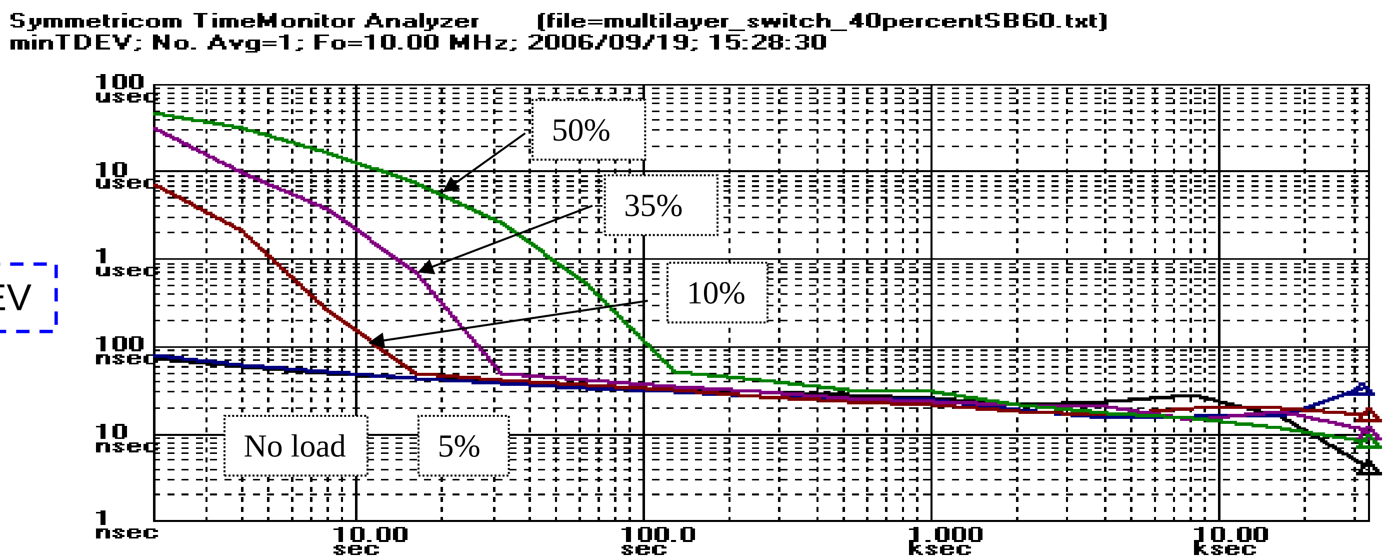
Symmetricom

TDEV

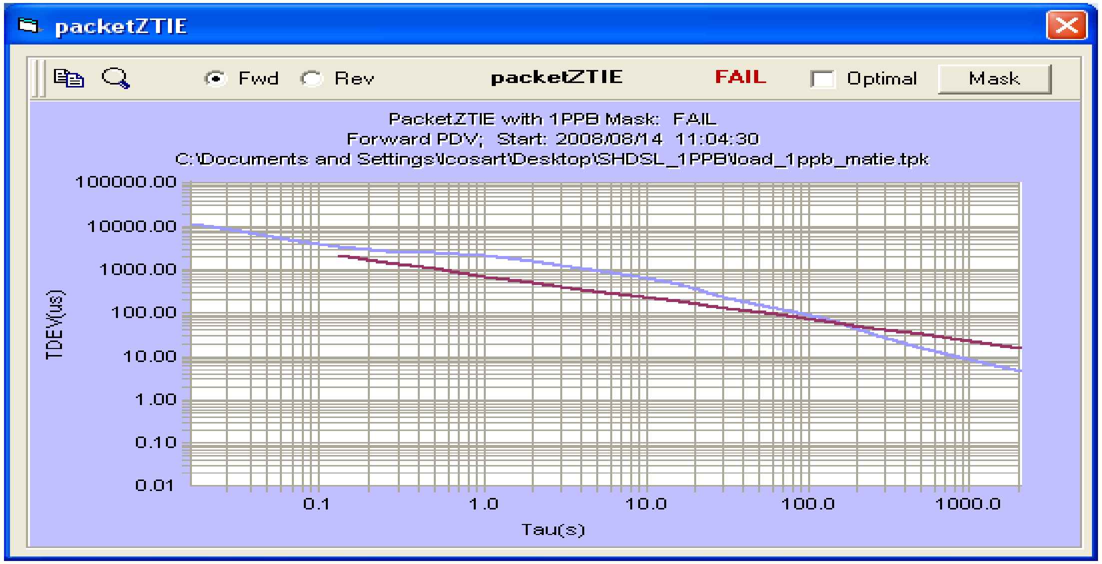



**Lower levels of noise with the application of a MINIMUM selection algorithm minTDEV at various traffic levels on a switch (0% to 50%) converge**

minTDEV

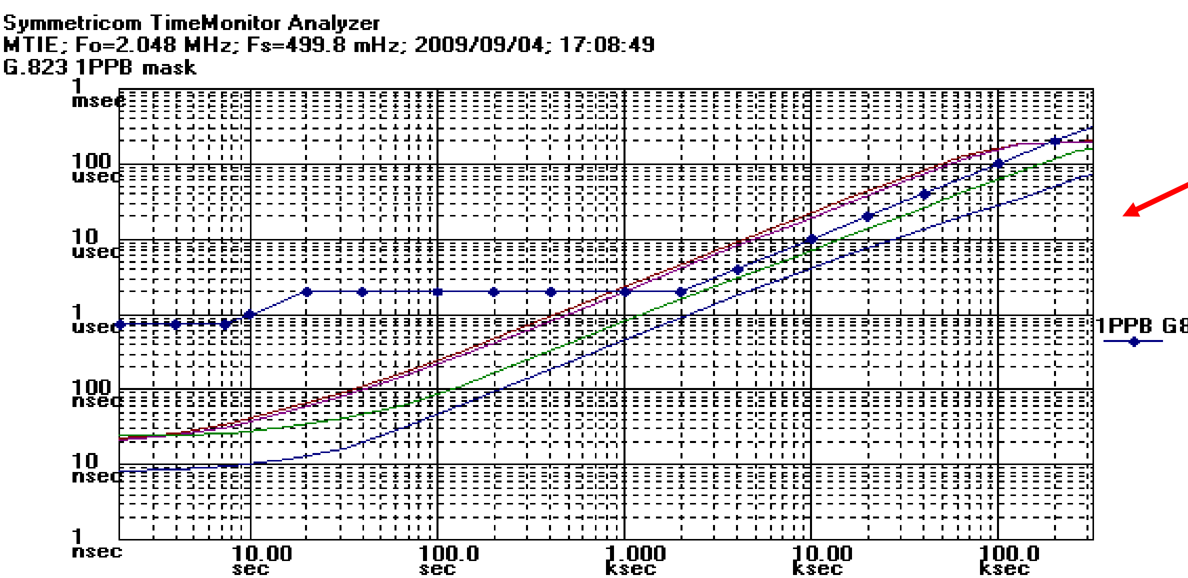


# MATIE and 1588 Slave Frequency Offset




Packet measurement

**Packet data analysis: 1PPB offset predicted**



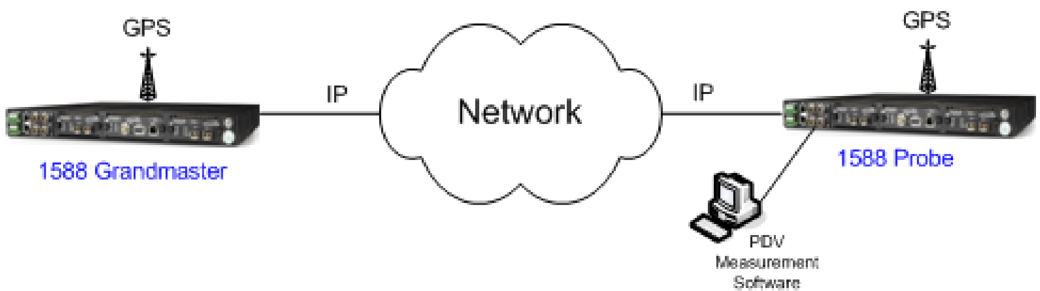

Sync measurement

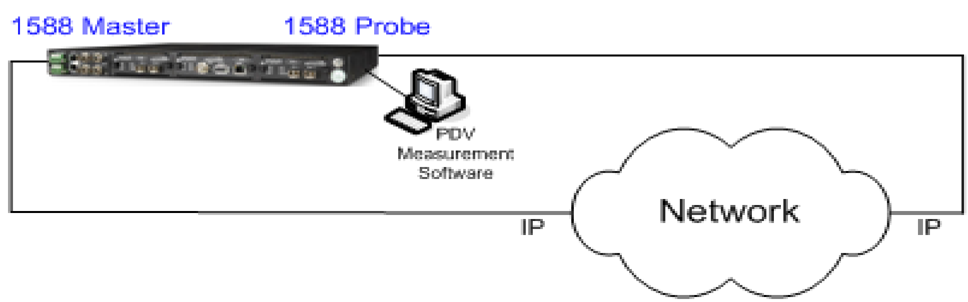
**1588 slave performance: 1 PPB offset measured**

# Packet Time Transport

## “PDV” measurement setup for time transport

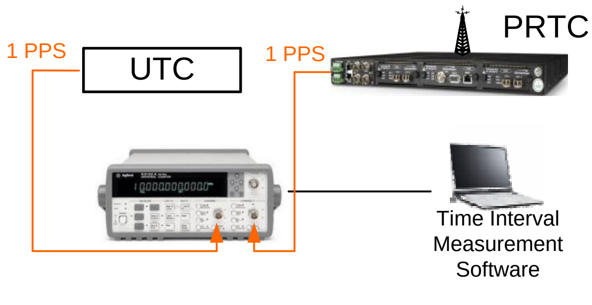
- Ideal setup - two packet timestampers with GPS reference so absolute latency can be measured as well as PDV over small to large areas
- Alternative setup (lab) – frequency (or GPS) locked single shelf with two packet timestampers
- Alternative setup (field) – frequency locked packet timestampers – PDV but neither <u>latency</u> nor <u>asymmetry</u> can be measured



# Time Metrics: Time Accuracy and Stability

## PRTC

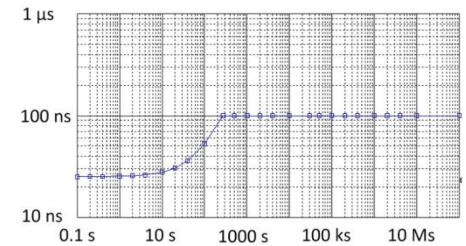



Time Accuracy

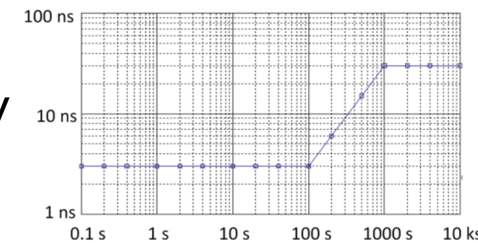
Time Error: <=100ns

Time Stability

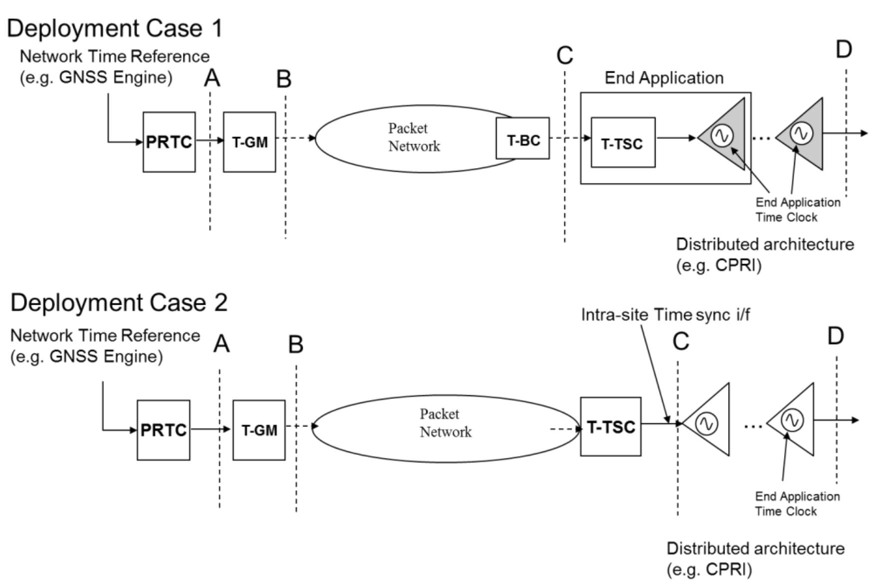
MTIE




TDEV




## Packet Network Limits




A: Time Error: <=100ns

C: Time Error: <=1.1µs

# 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 |

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

**Minimum Search Sequence**

| 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 | | |

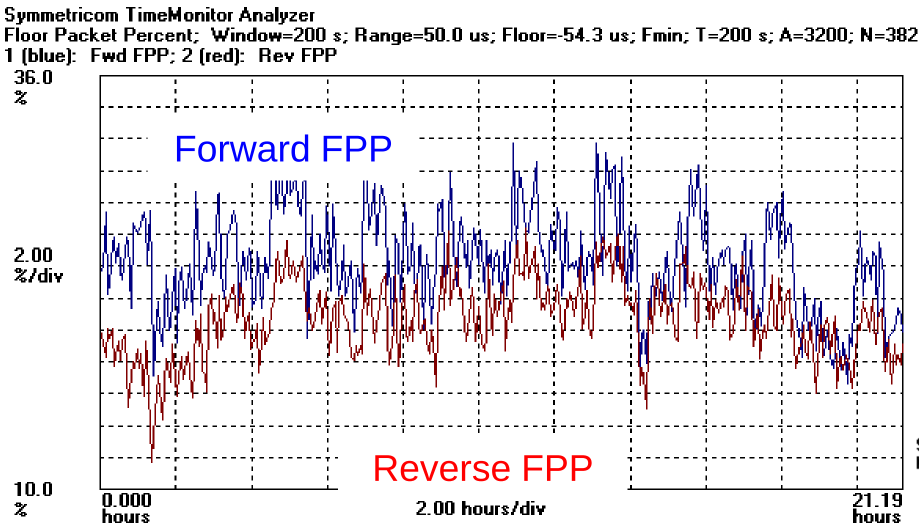
**minOffset**

| | |
|---|---|
| 0.1 | 0.07 |
| 0.4 | 0.18 |

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

# Metrics: Time Transport

Forward/Reverse FPP



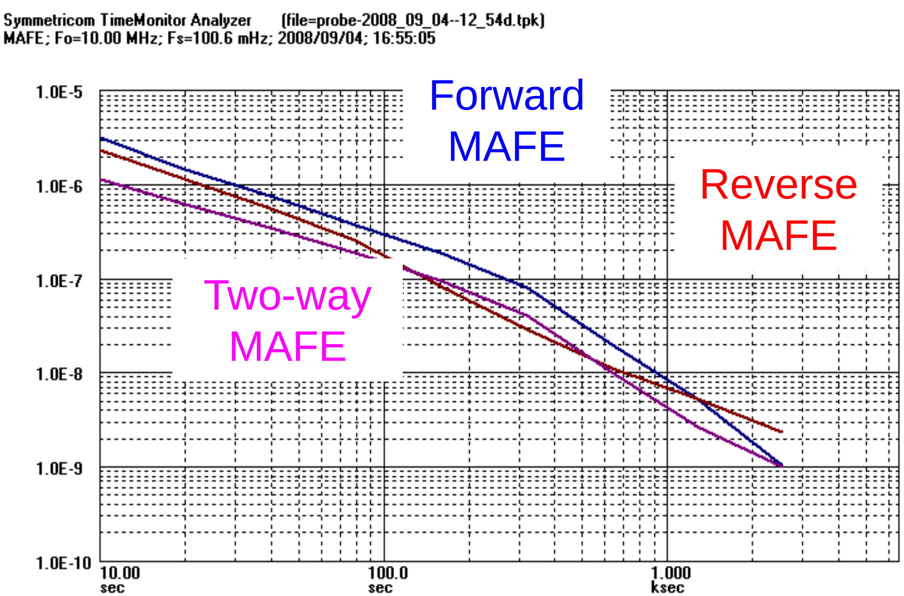

Approaches:

(1) Based on both one-way sequences

(2) Based on a single sequence constructed from both one-way sequences (e.g. offset)

Two-way MAFE

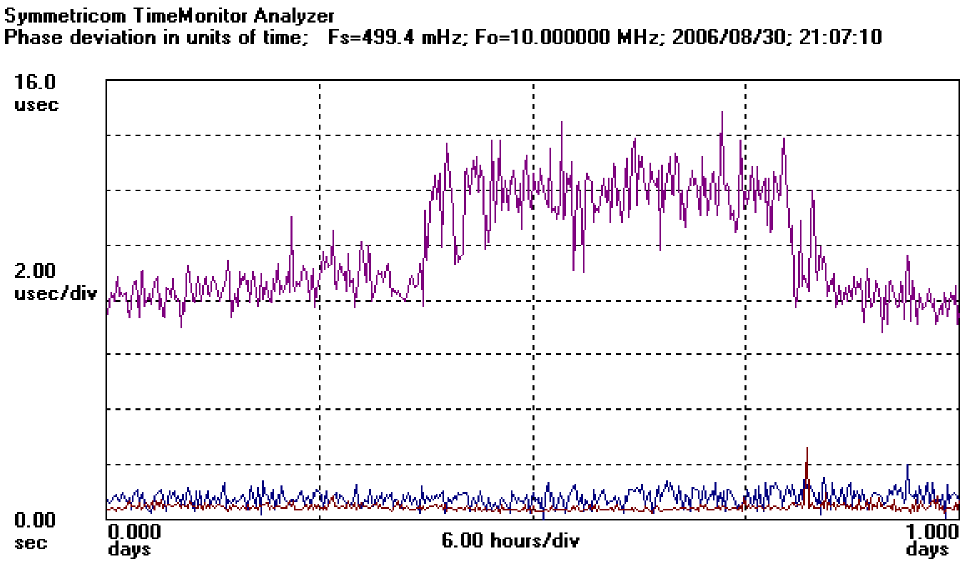
(MAFE of minOffset)



# Case Studies: Five Networks

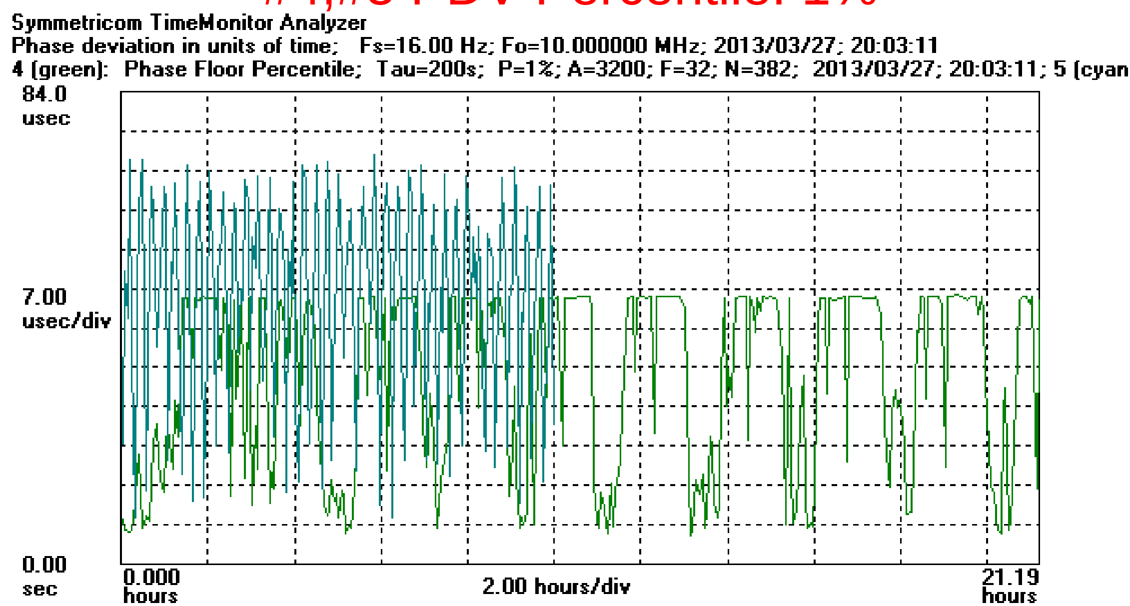
Symmetricom

## #1,#2,#3 PDV Percentile: 1%




What FPP level could be set to get at least 1% of the packets?

## #4,#5 PDV Percentile: 1%

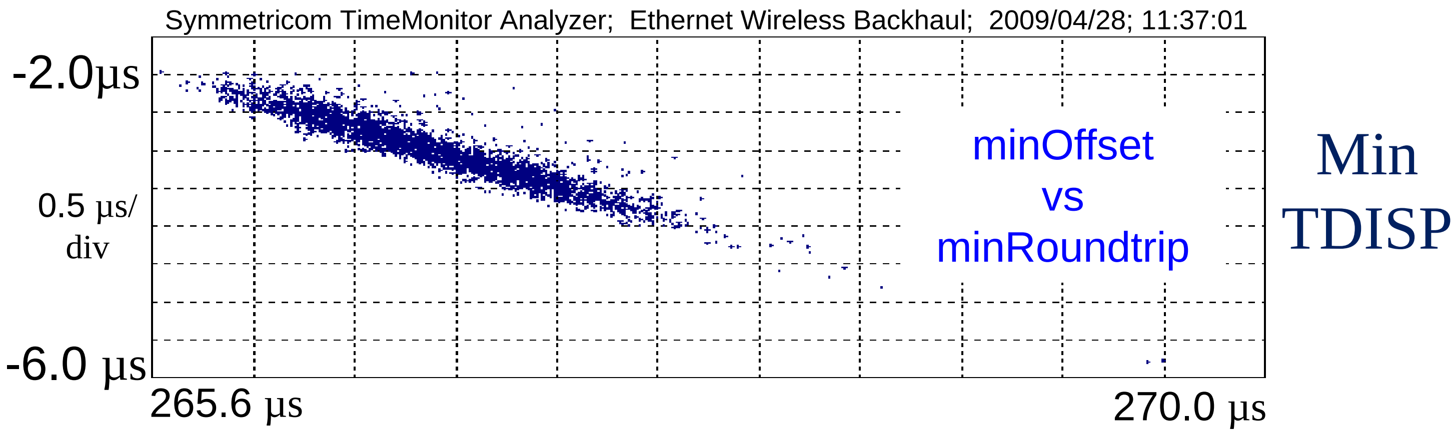


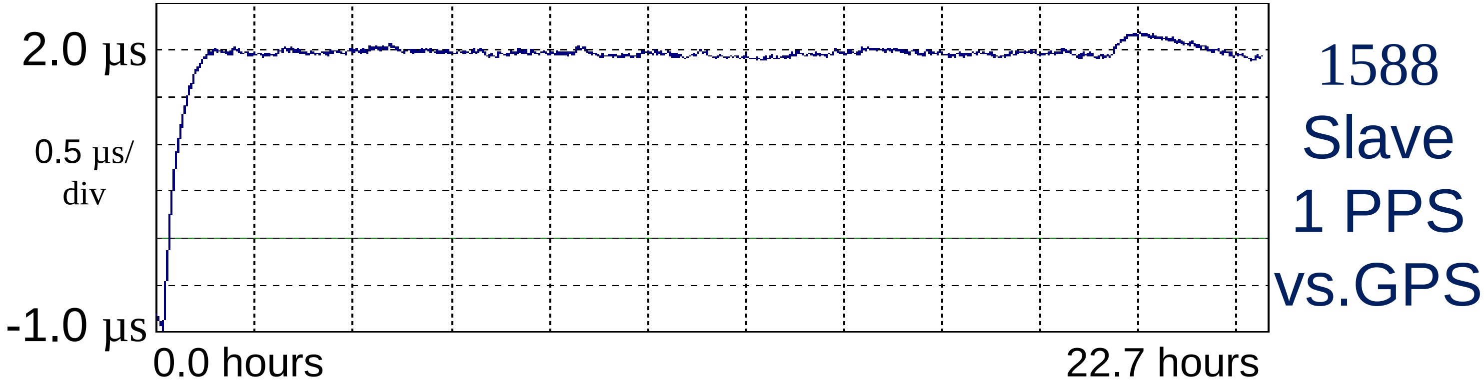

| | Max 1 Percentile |
|---|---|
| U.S. Ethernet south | 2.04 µsec |
| U.S. Ethernet north | 2.60 µsec |
| Backhaul N America | 13.8 µsec |
| Eth/SONET | 47.8 µsec |
| Backhaul Europe | 72.6 µsec |

# Case Studies: Network Time Transport

## Asymmetry in Wireless Backhaul

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



# 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
    - Accuracy vs. stability
    - Stability analysis from (1) both one-way or (2) combined sequence

- Measurement Case Studies
  - Networks
    - Five networks
    - Network time transport

# Thank You

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