ACS Timing Product Group

Network Metrics

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Presentation Outline

- Rationale for Network Metrics: Can the network support synchronization? If so, what quality level can be supported?
  - Underlying principles of timing over packet networks
    - Theoretical basis
    - Primary cause of inaccuracy is packet delay variation (PDV)
- Metrics
  - TDEV, min_TDEV
  - Spread-separation
- Examples
  - Gamma density function (white noise)
  - 8-switch simulation with different loads (based on G.8261)
- Approximations of min_TDEV

Timing over packet - principle

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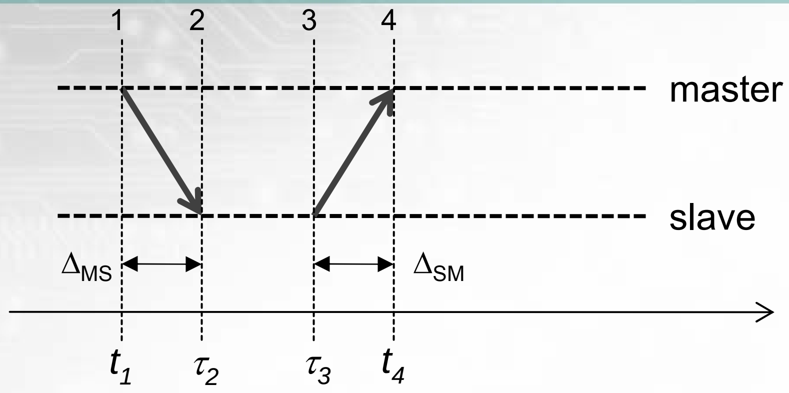


Slave time offset: $t = \tau + \varepsilon$

RTD = round-trip delay

$$\varepsilon = \left(\frac{1}{2}\right)(t_4 - \tau_3 - \tau_2 + t_1)$$

$$RTD = (t_4 - \tau_3 + \tau_2 - t_1)$$

Time offset estimate based on two packets (two-way)

Assumption: $$\Delta_{MS} = \Delta_{SM} = \left(\frac{1}{2}\right)\cdot(t_4 - \tau_3 + \tau_2 - t_1) = \left(\frac{1}{2}\right)\cdot RTD$$

error: $$\Delta\varepsilon = \left(\frac{1}{2}\right)(\Delta_{MS} - \Delta_{SM})$$

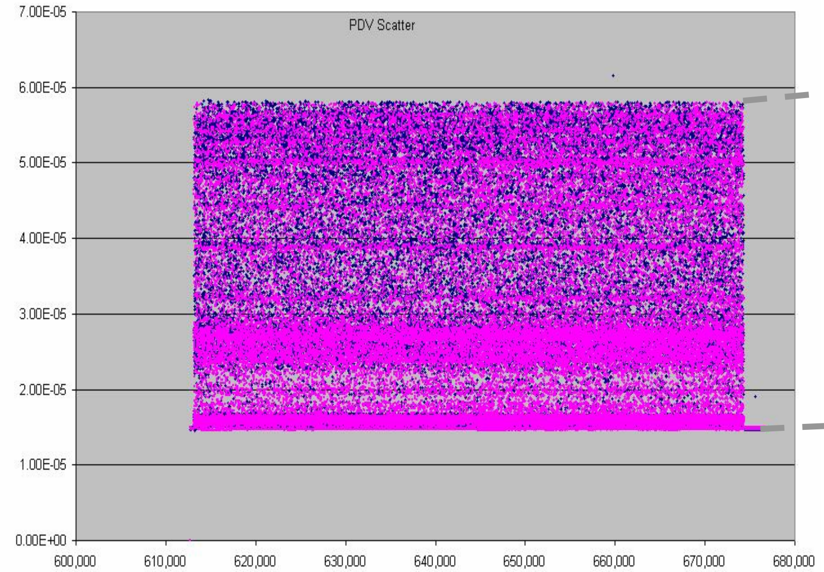
Time offset estimate error caused by *asymmetry* in transit delay

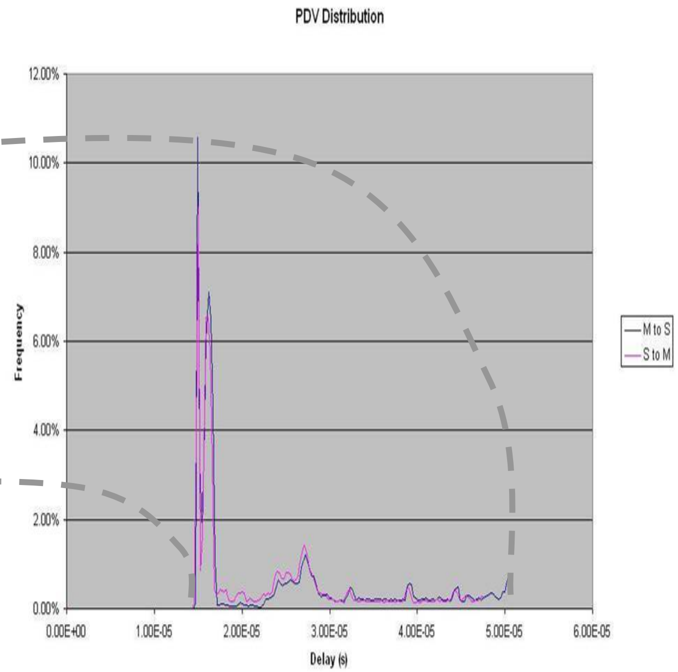
Frequency offset estimate based on two packets (one-way):

$$\Delta\hat{y} = \frac{(t_1(n_2) - t_1(n_1)) - (\tau_2(n_2) - \tau_2(n_1))}{(t_1(n_2) - t_1(n_1))} = \Delta y - \frac{(\Delta_{MS}(n_2) - \Delta_{MS}(n_1))}{(t_1(n_2) - t_1(n_1))}$$

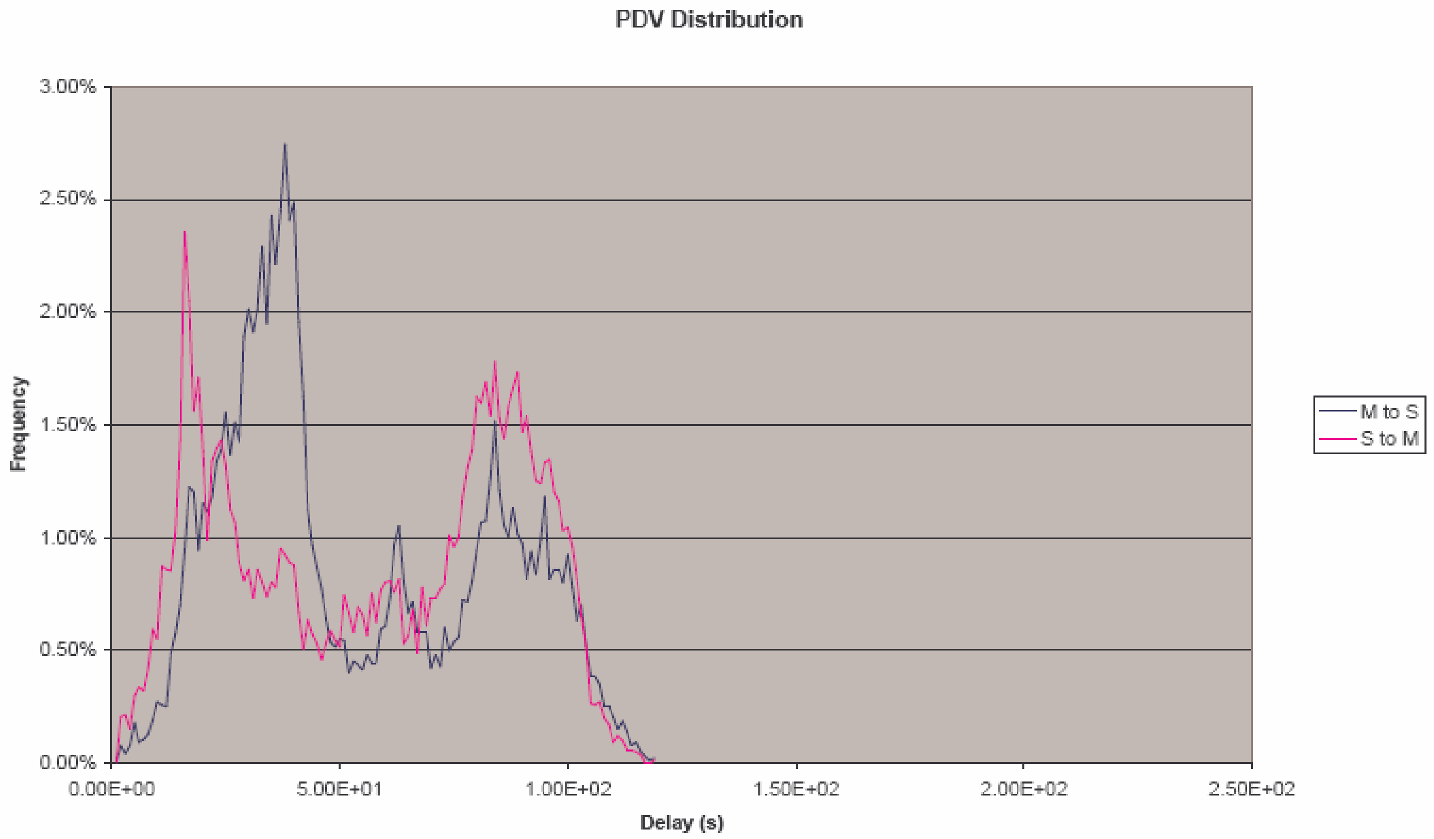
Frequency offset estimate error caused by *packet delay variation*

Timing transfer without intermediate clocks

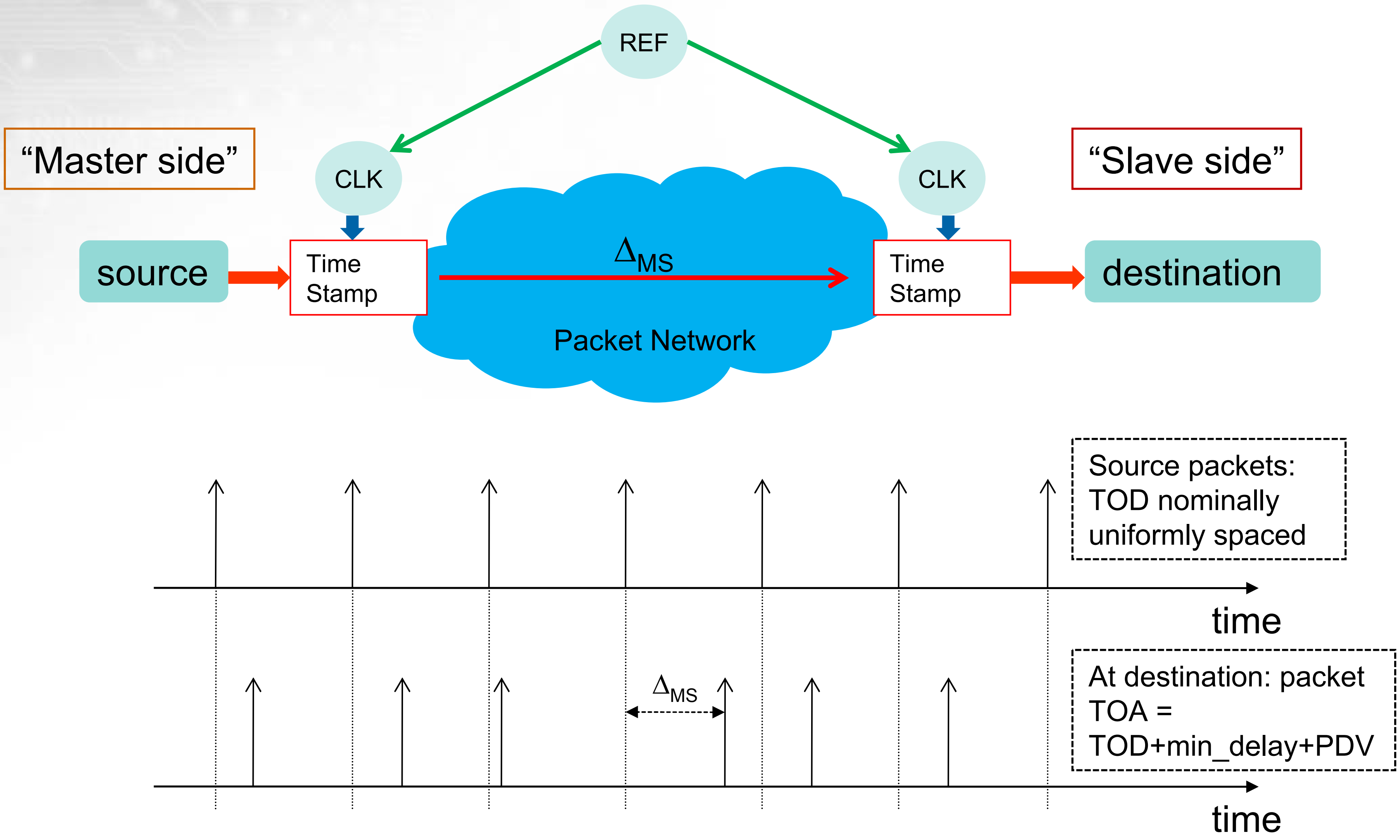




PDV is not always so easy to work with......



Network Measurement



Network metrics

- Based on measurements of transit delay
  - $\Delta_{MS}(n)$ = transit delay of n^{th} packet
  - $\Delta_{MS}(n) = \Delta_0 + x(n)$
    - Δ_0 = minimum delay (propagation)
    - $x(n)$ = packet delay variation (*aka* IPDV) (non-negative random variable)
  - Assume that inter-packet interval is (approximately) constant
    - $\{x(n)\} = \{x(nT_0)\}$ (discrete-time signal with implied sampling rate of $f_0 = 1/T_0$)
- Errors caused by non-zero nature of $\{x(n)\}$:
  - Error in estimation of minimum delay (Δ_0) affects *time*
  - Variability of $x(n)$ affects *frequency* (and time)
    - White noise component can be reduced by averaging
    - Oscillator performance restricts averaging time
    - Short-term slope in $\{x(n)\}$ affects slave frequency offset estimate
- Metrics quantify the "non-zero" nature of $\{x(n)\}$
  - Permissible to ignore (some) packets deemed to have excessive delay variation

Network Metrics (spread-separation)

- Intent of spread-separation metrics:
  - Identify the extent to which packets that have excess delay variation can be discarded
  - Retained packets are not uniformly spaced in time
- Basis: For a given Δ, discarding packets with delay > Δ is permissible provided that
  - The number of packets retained is statistically significant.
  - The time interval over which there are no packets retained is sufficiently small. That is, there should not be large time gaps in the non-discarded data.
- Given a data set of N points, $\{x_i;\ i = 0,1,2,\ldots,(N-1)\}$ with implied sampling interval T_0 with $\min[x_i] = \Delta_0$:
  - Construct the set $\{i_k;\ k=0,1,\ldots,(K-1)\}$ defined by $\Delta_0 \le x_i \le \Delta_0 + \Delta$
  - Spread-separation probability (Δ) = (K/N)
  - Spread-separation-sigma $\sigma_{SS}(\Delta)$ = std. dev. of $\{(i_{(k+1)} - i_k)\}$
    - Spread-separation-maximum = max. $\{(i_{(k+1)} - i_k)\}$; (max ≈ $4 \cdot \sigma_{SS}(\Delta)$)

TDEV, min_*TDEV* - *definition*

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- Given a data set of *N* points, $\{x_i;\ i = 0,1,2,\ldots,(N-1)\}$ with implied (equi-spaced) sampling interval τ_0:

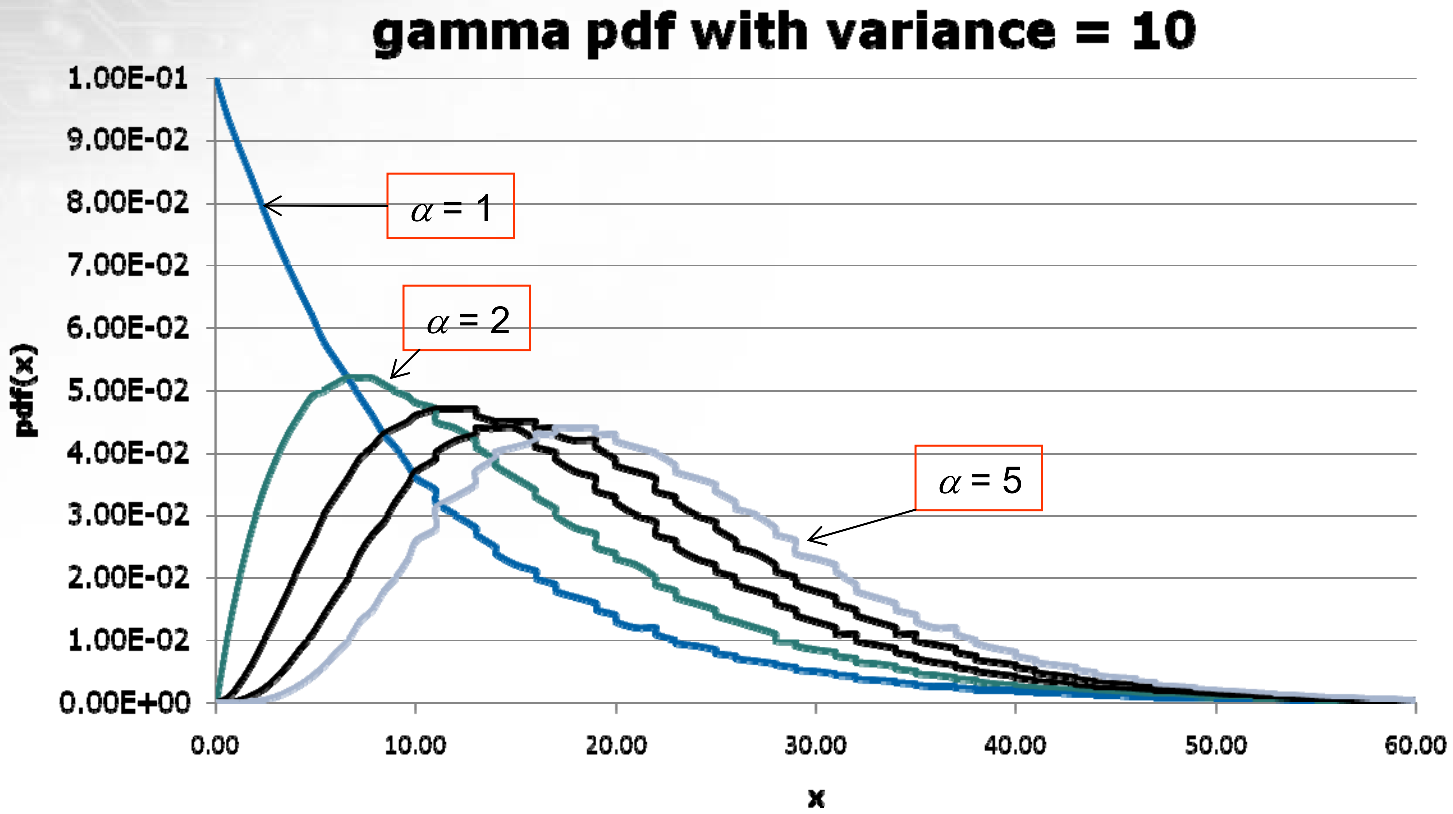
- $TDEV(\tau = n\cdot\tau_0)$ is defined as:

$$[TDEV(\tau)]^2 = \frac{1}{6(N-3n+1)}\sum_{j=0}^{N-3n}\left[\frac{1}{n}\sum_{i=j}^{n+j-1}(x_{i+2n} - 2x_{i+n} + x_i)\right]^2$$

- min_$TDEV(\tau = n\cdot\tau_0)$ is defined as:

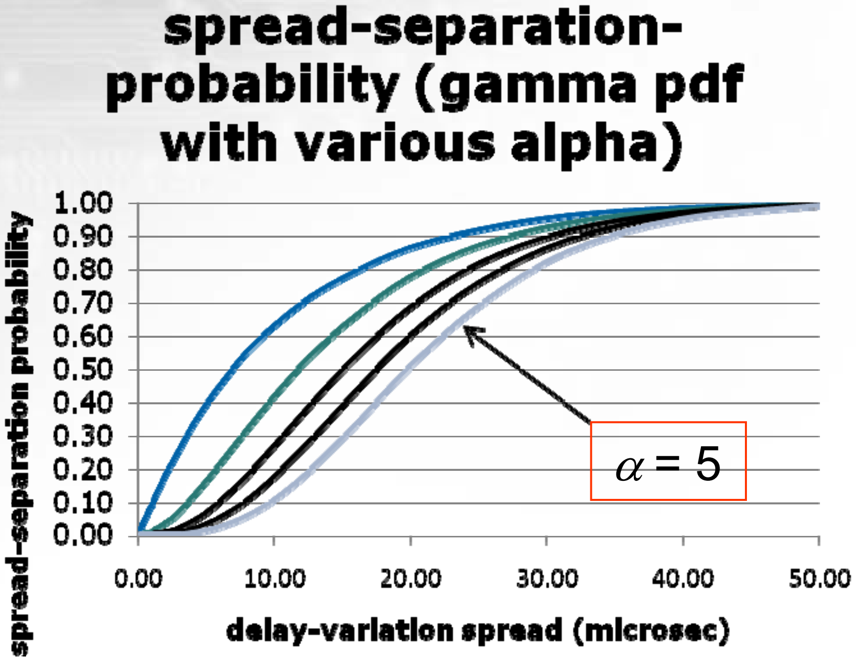
$$[\min\_TDEV(\tau)]^2 = \frac{1}{6(N-3n+1)}\sum_{j=0}^{N-3n}\begin{bmatrix}\min\{(x_{i+2n});\ j \le i \le (n+j-1)\} - \\ 2\min\{(x_{i+n});\ j \le i \le (n+j-1)\} + \\ \min\{(x_i);\ j \le i \le (n+j-1)\}\end{bmatrix}^2$$

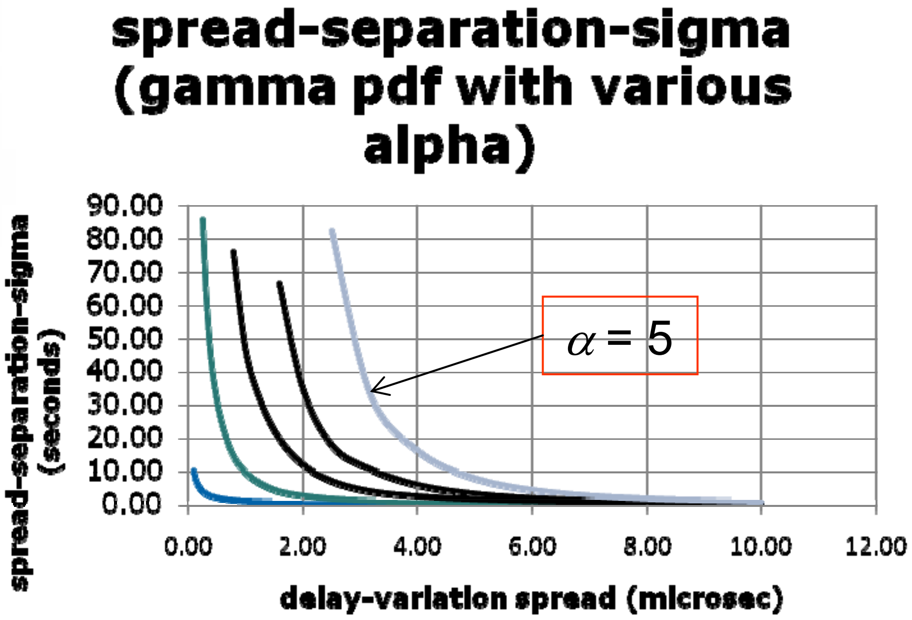
Gamma pdf



Synthetic PDV data generated with a gamma pdf for different values of α (1,2,3,4,5) and β chosen to keep standard deviation = 10 μs. Note that skewness decreases with increasing α ; a large value of skewness is preferred for timing recovery. Implicit sampling interval is 100ms (10 packets per second).

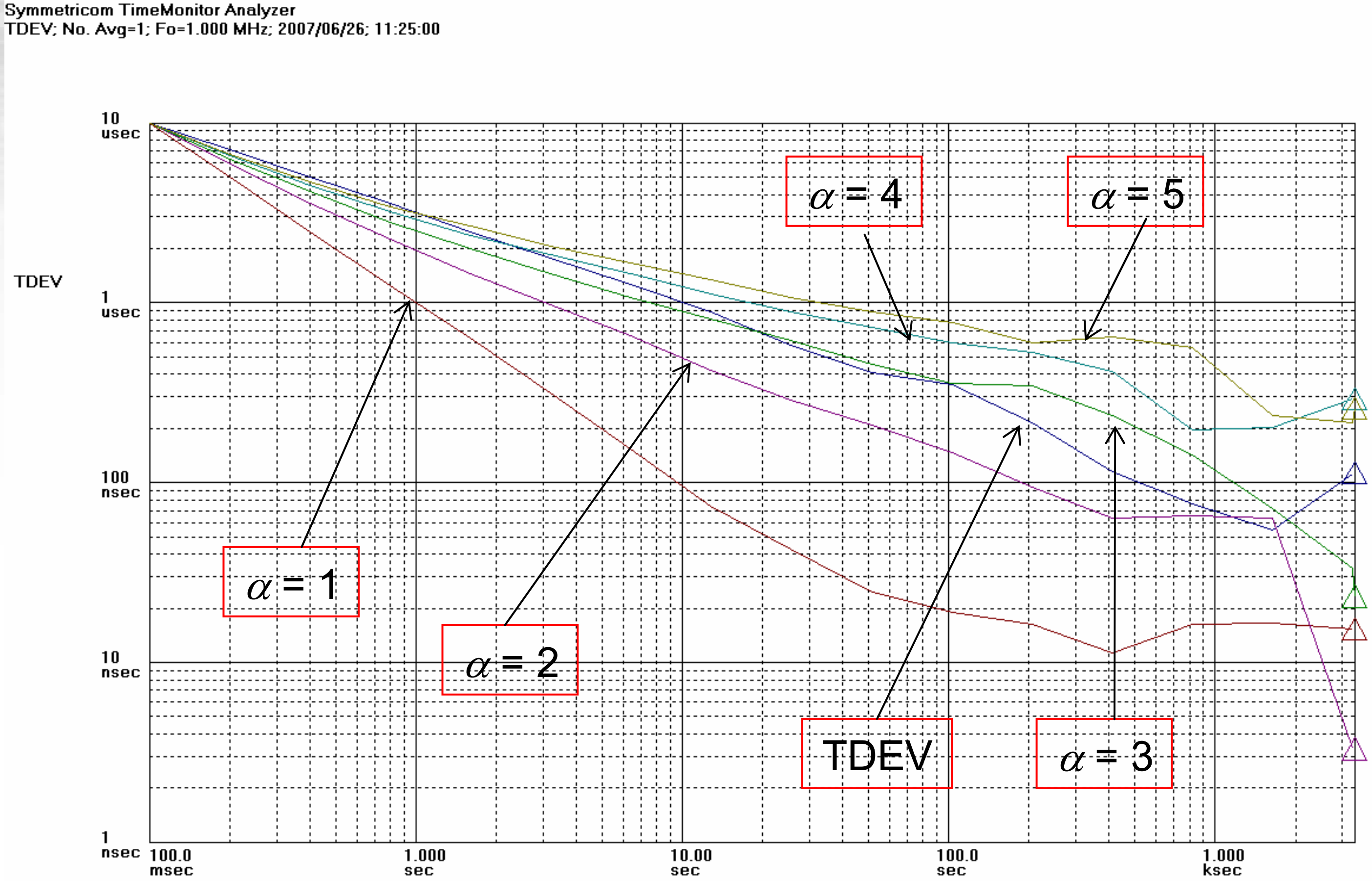
Spread-separation metrics (gamma pdf)





Spread-separation-sigma provides a clear indication of the skewness of the PDV distribution. Spread-separation-probability provides guidance as to the PDV threshold applicable for packet selection.

min_*TDEV* for Gamma pdf



The slope of min_TDEV compared to TDEV provides an indication of skewness of the PDV distribution.

Simulation Exercises - pdf

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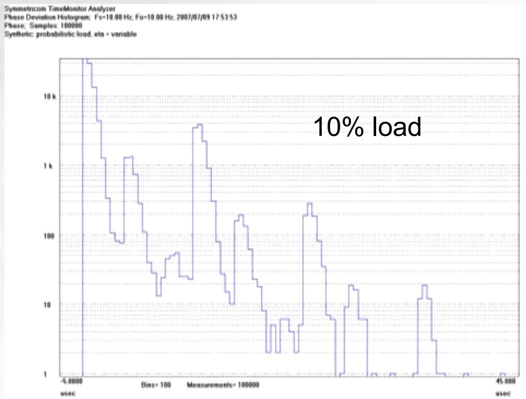
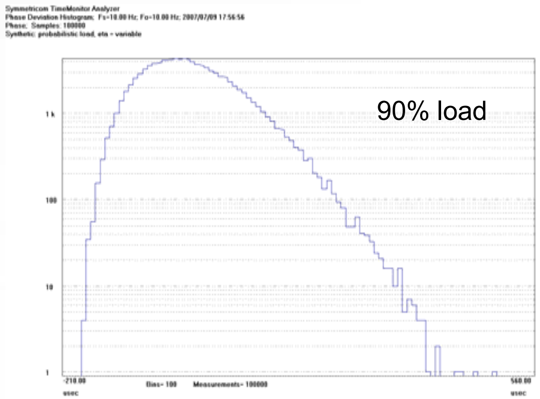
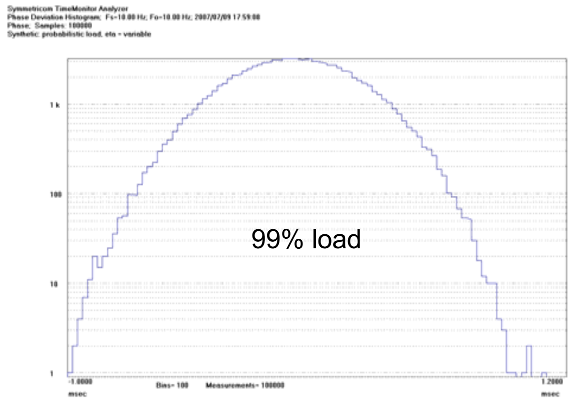
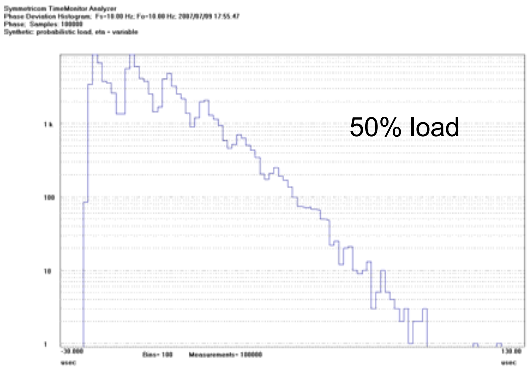
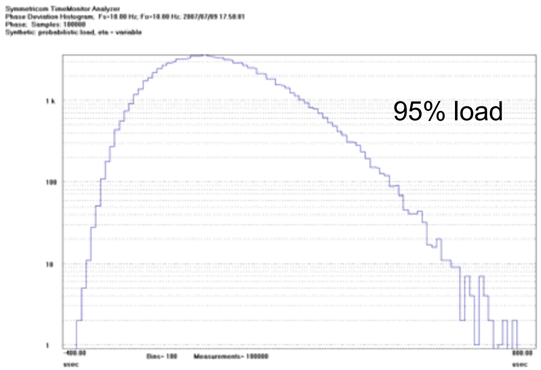
Simulation of 8 switches and varying load (G.8261 Model 1 used for traffic pattern)







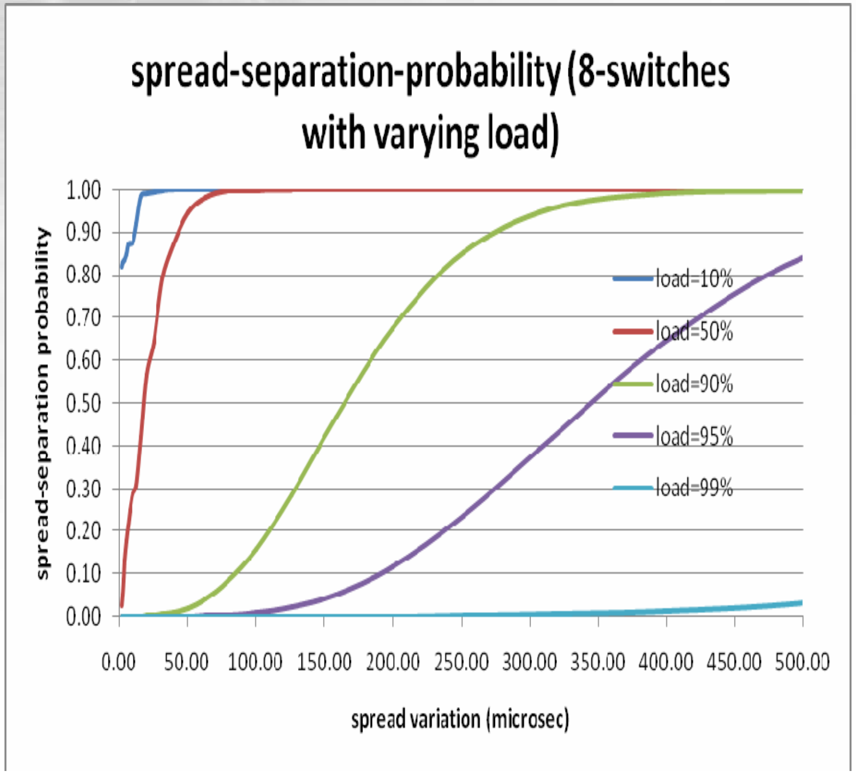


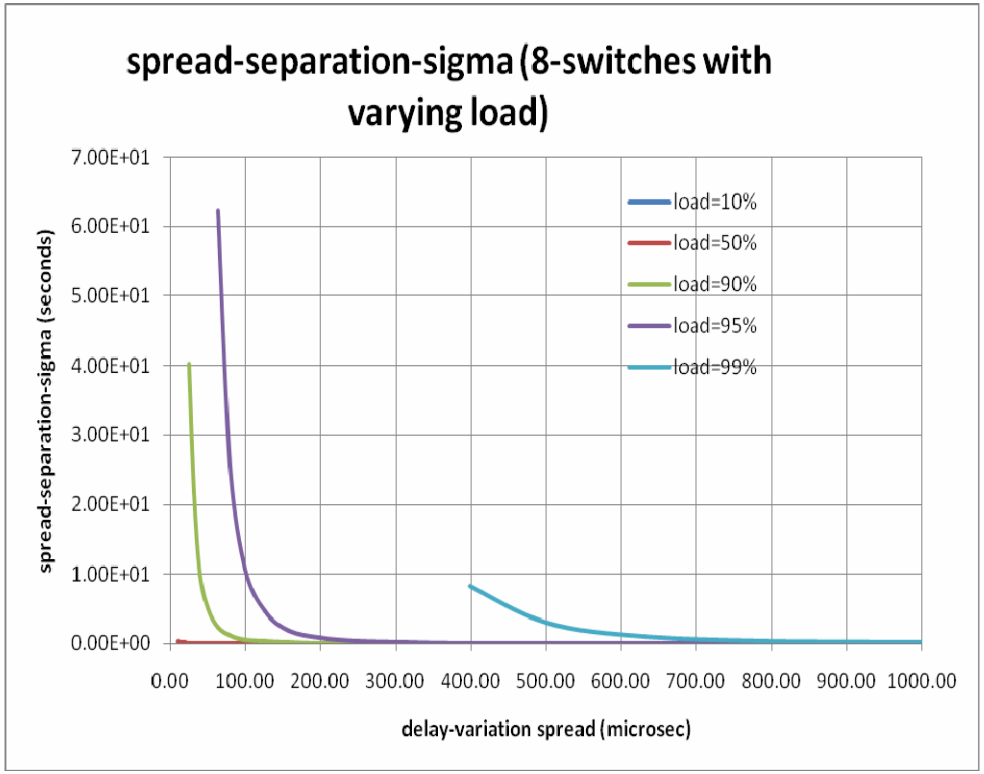


Clearly, increasing load leads to:
- ❖Increase in mean value
- ❖Increase in variance
- ❖Decrease in skewness

Probability distribution functions for the 5 cases simulated.
Assumed line rate = 1 Gb/s; clock noise (below SEC mask) added

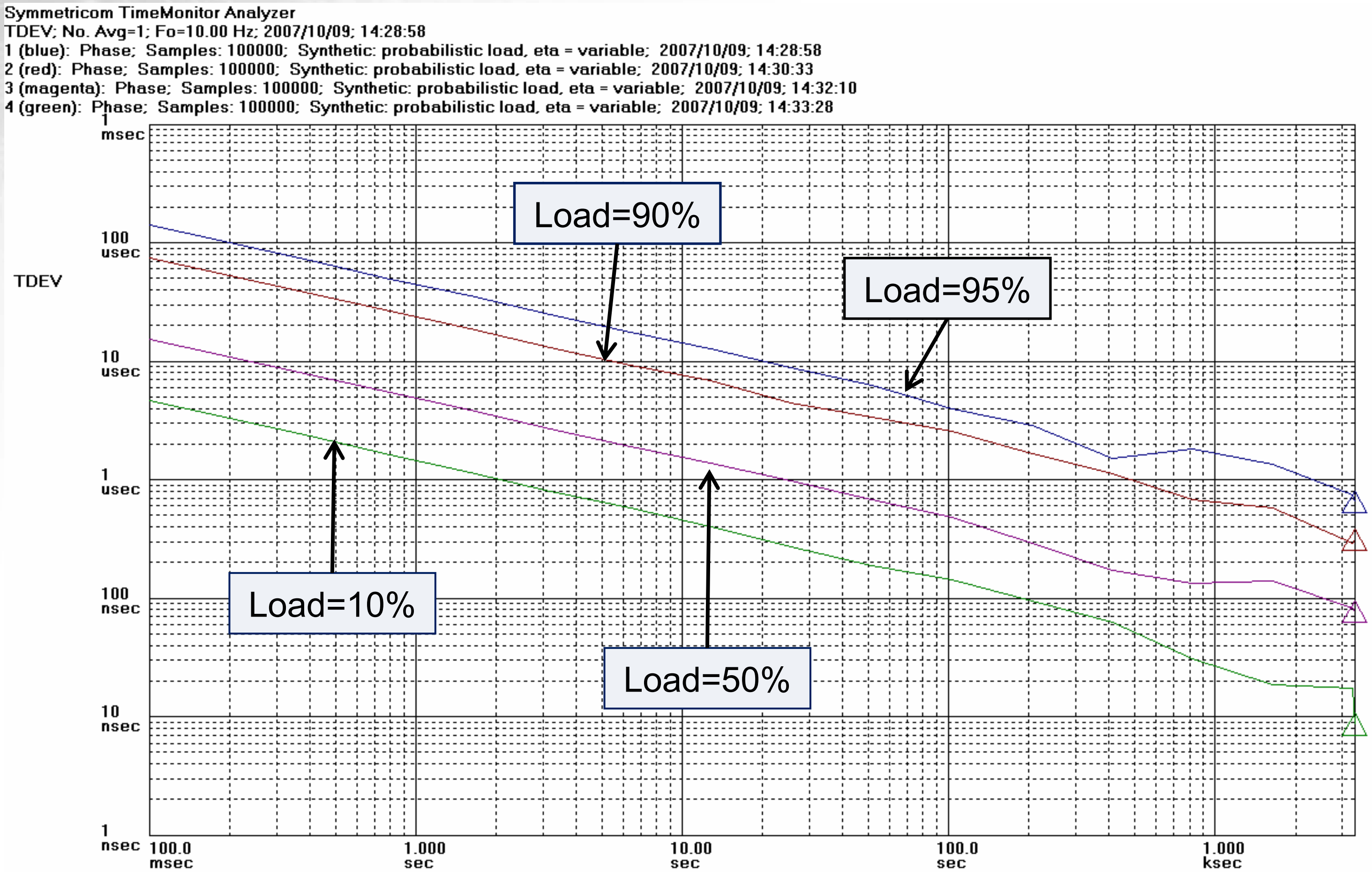
Simulation Exercises – Delay-spread





Observation: spread-separation metrics can identify the increase in variance and the decrease in skewness associated with increasing load.

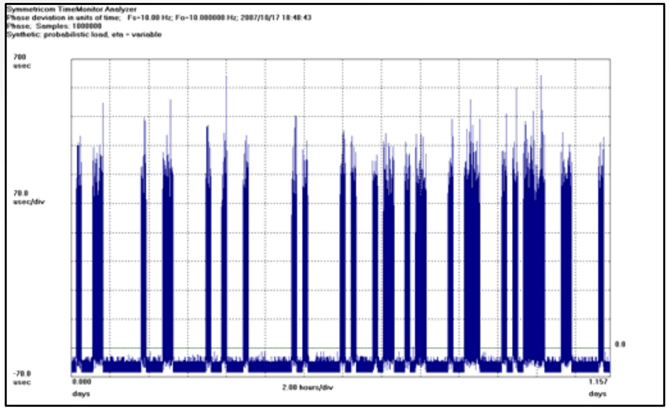
Simulation Exercise - TDEV



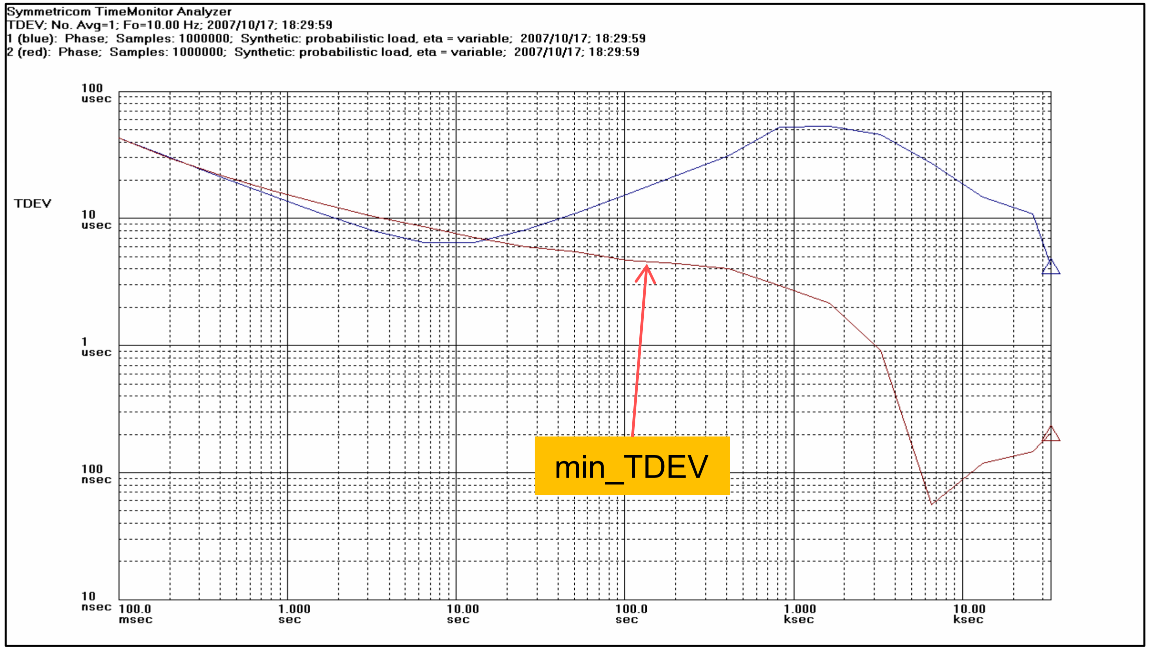
Observation: constant load generates a white-PM packet delay variation. TDEV can identify increase in variance (but not skewness) associated with change in load.

Simulation exercise – varying load

- Load is either 10% or 90% with probability 0.7 and 0.3
- Load changed on 1000s boundary
- TDEV reflects the quasi-periodic behaviour of the PDV

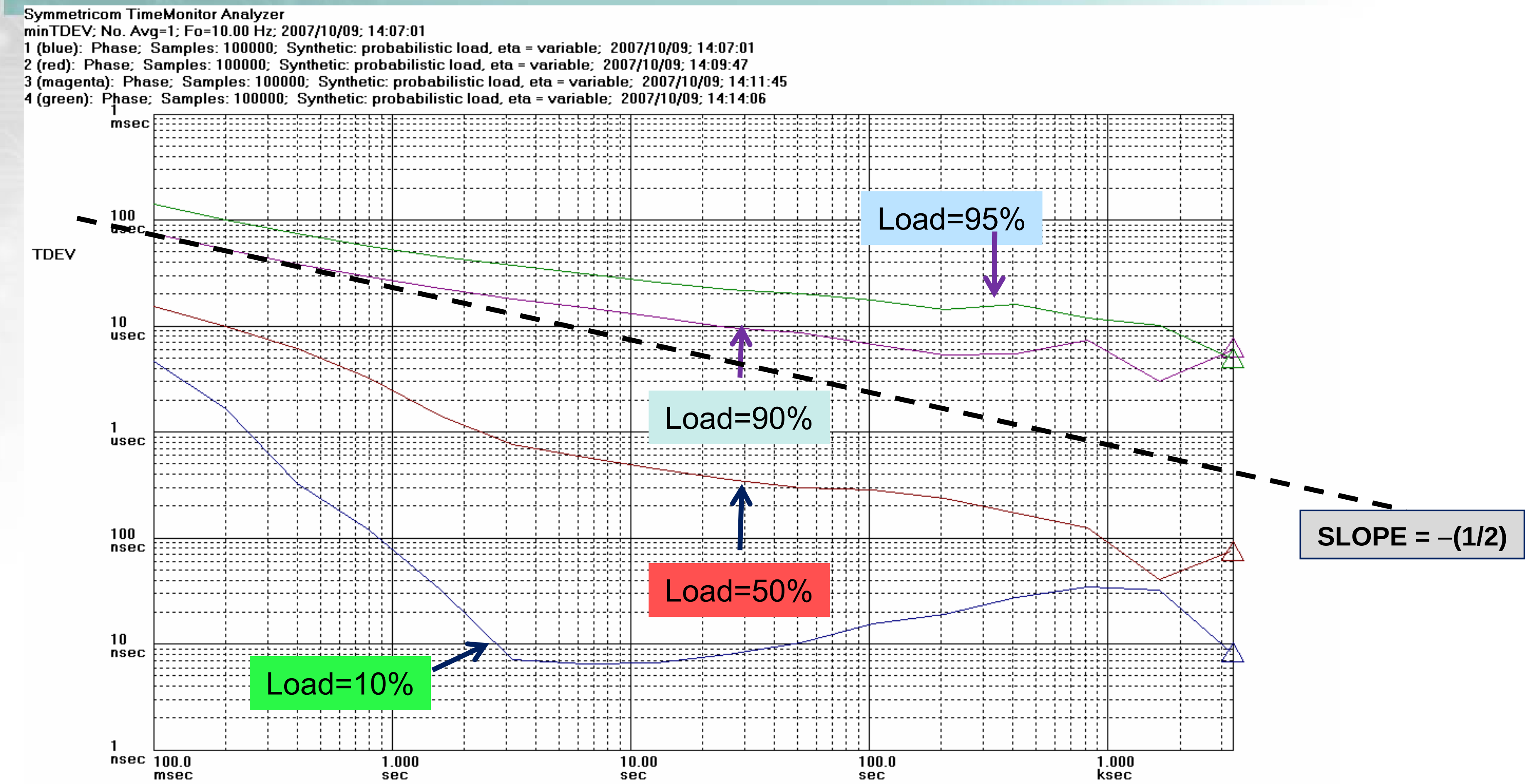


Phase plot showing the change in PDV characteristics on 1000s boundaries



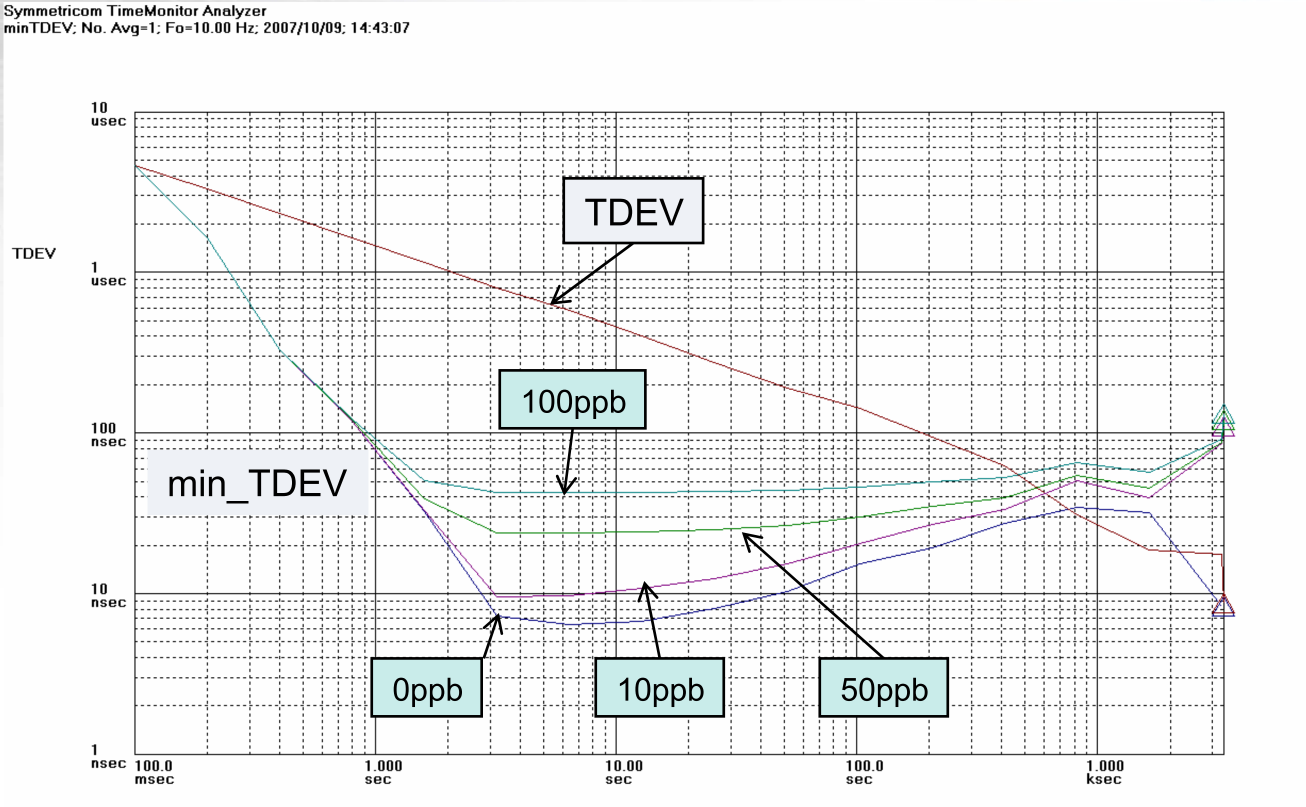
TDEV and min_TDEV

Simulation exercise - min_TDEV



min_TDEV can identify load (variance) as well as indicate skewness

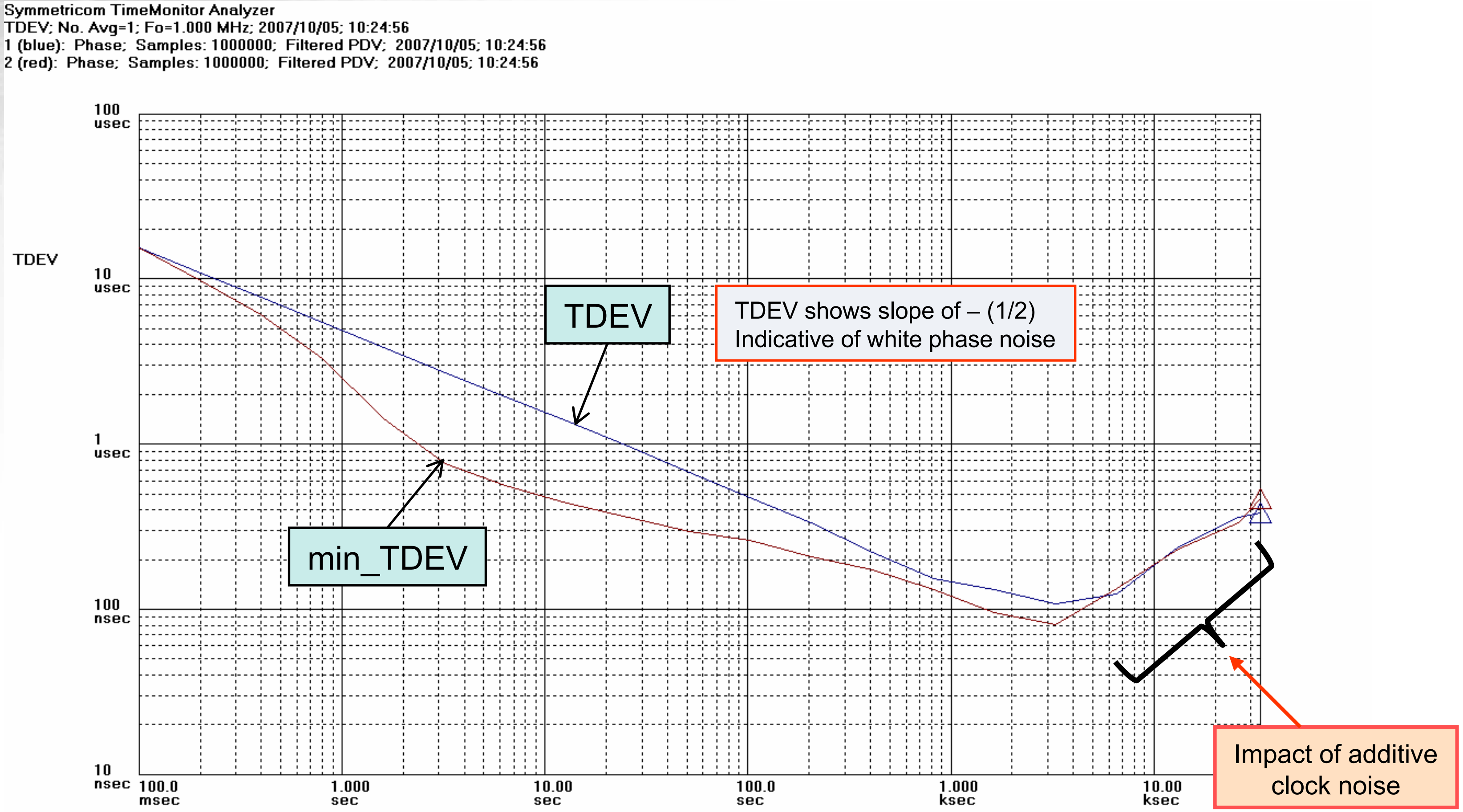
Impact of frequency offset



Simulation with load = 10% ; added frequency offset = 0ppb, 10ppb, 50ppb, 100ppb.

- TDEV is not affected by frequency offset.
- min_TDEV and spread-separation metrics are affected by frequency offset.

Approximations of min_TDEV



TDEV and min_TDEV computed for scenario with 50% load plus clock noise (below SEC mask)

Approximations of min_TDEV

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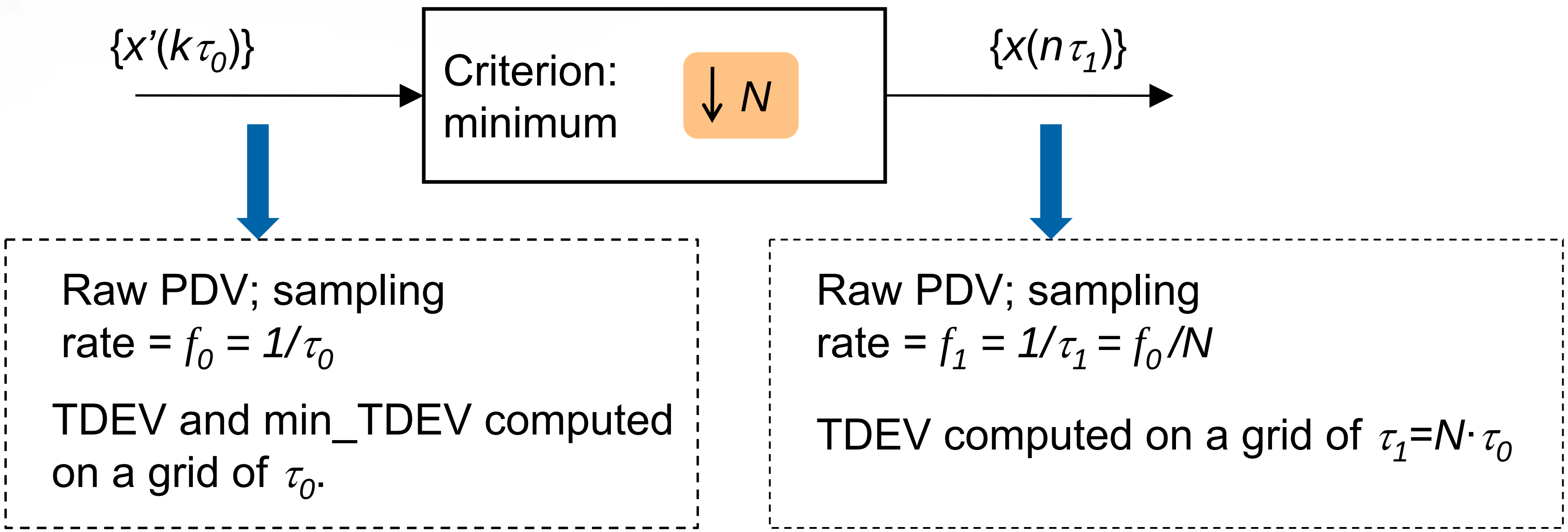
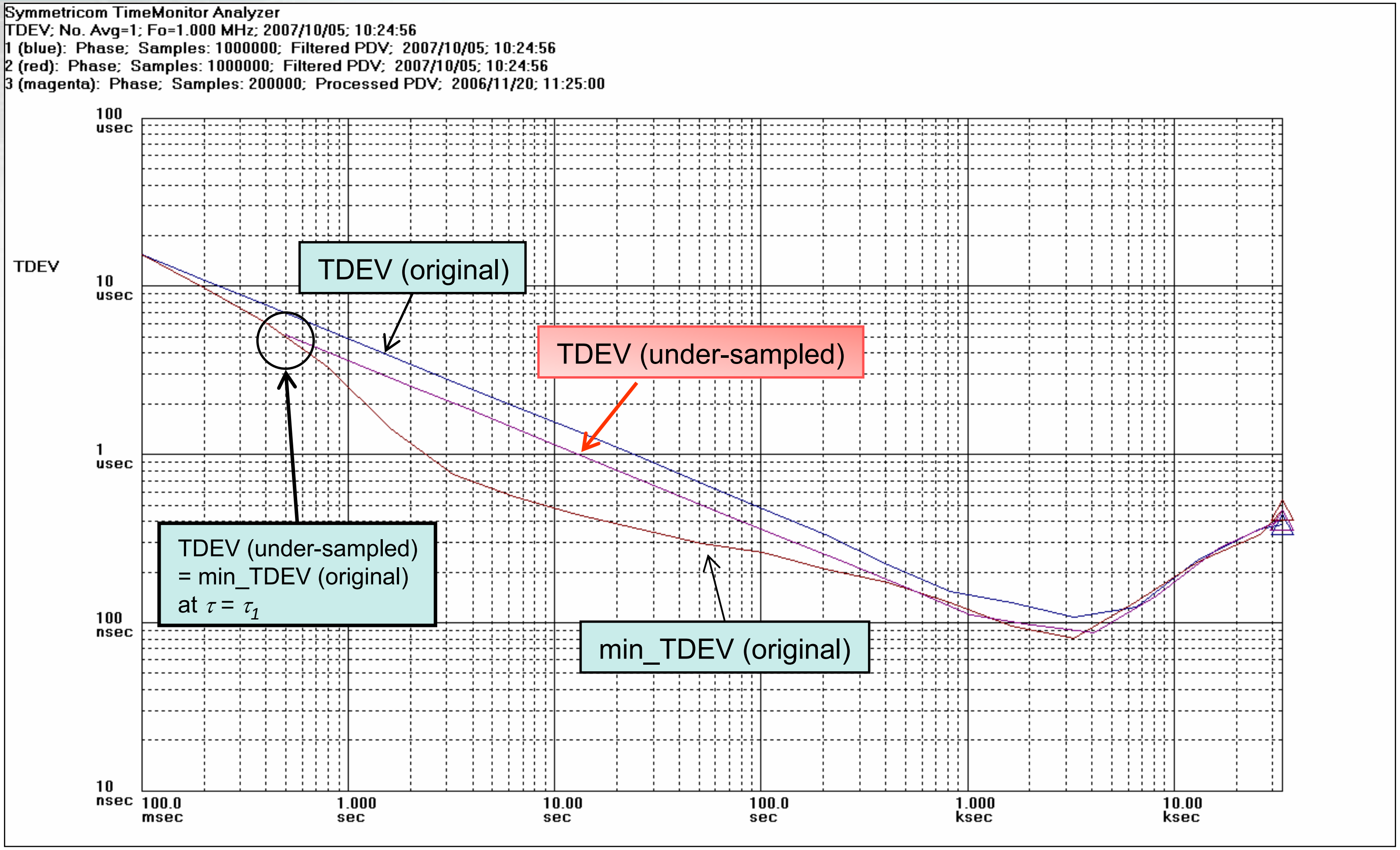
- TDEV and min_TDEV are computed on the entire data-set corresponding to a sampling rate of $f_0 = 1/\tau_0$
- Approximations to min_TDEV can be obtained by computing the TDEV on a reduced data-set corresponding to under-sampling by a factor of N
  - Choose minimum value out of every N samples



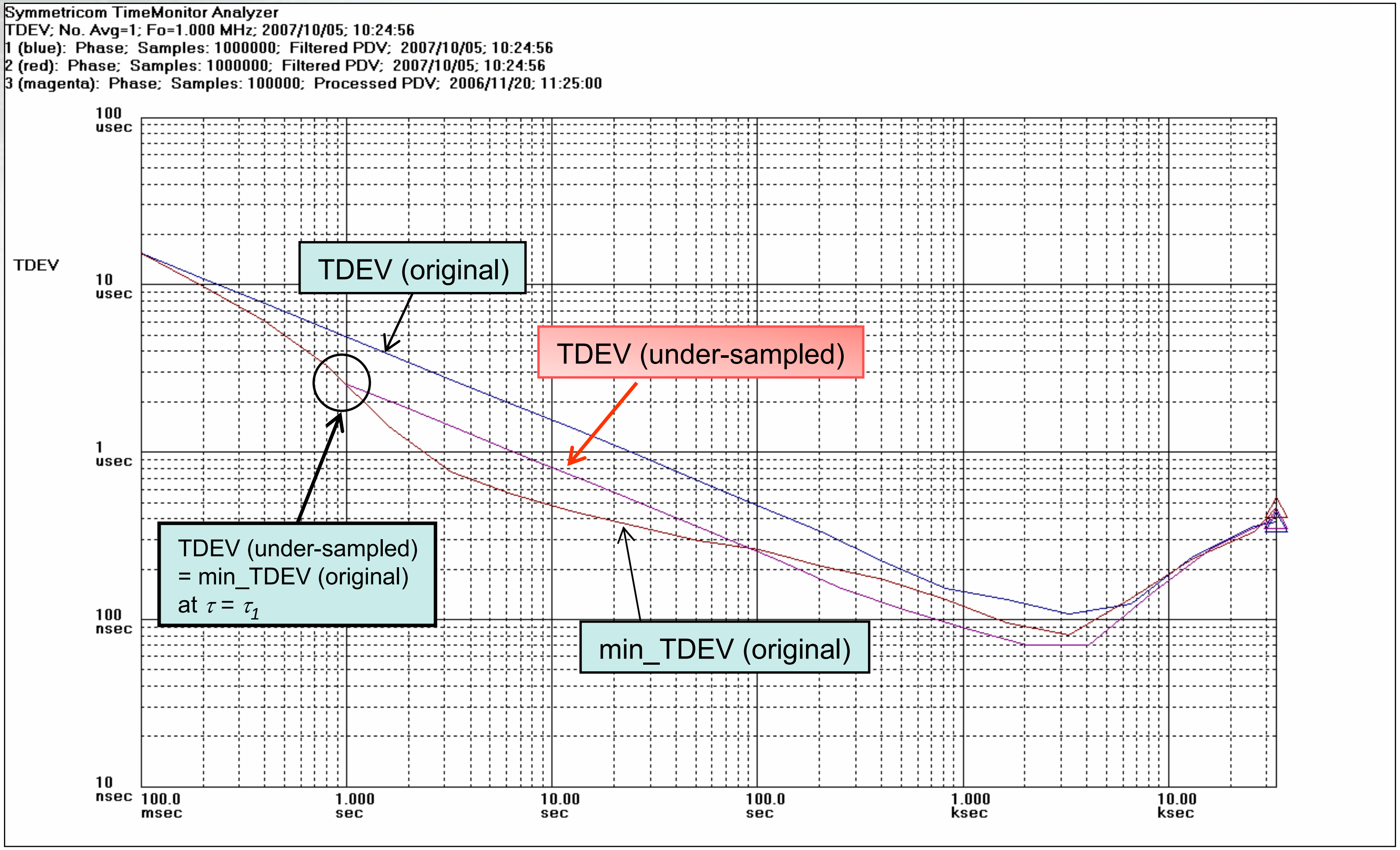
Approximations of min_TDEV



Under-sampling factor = 5

τ_0 = 100ms; τ_1 = 500ms

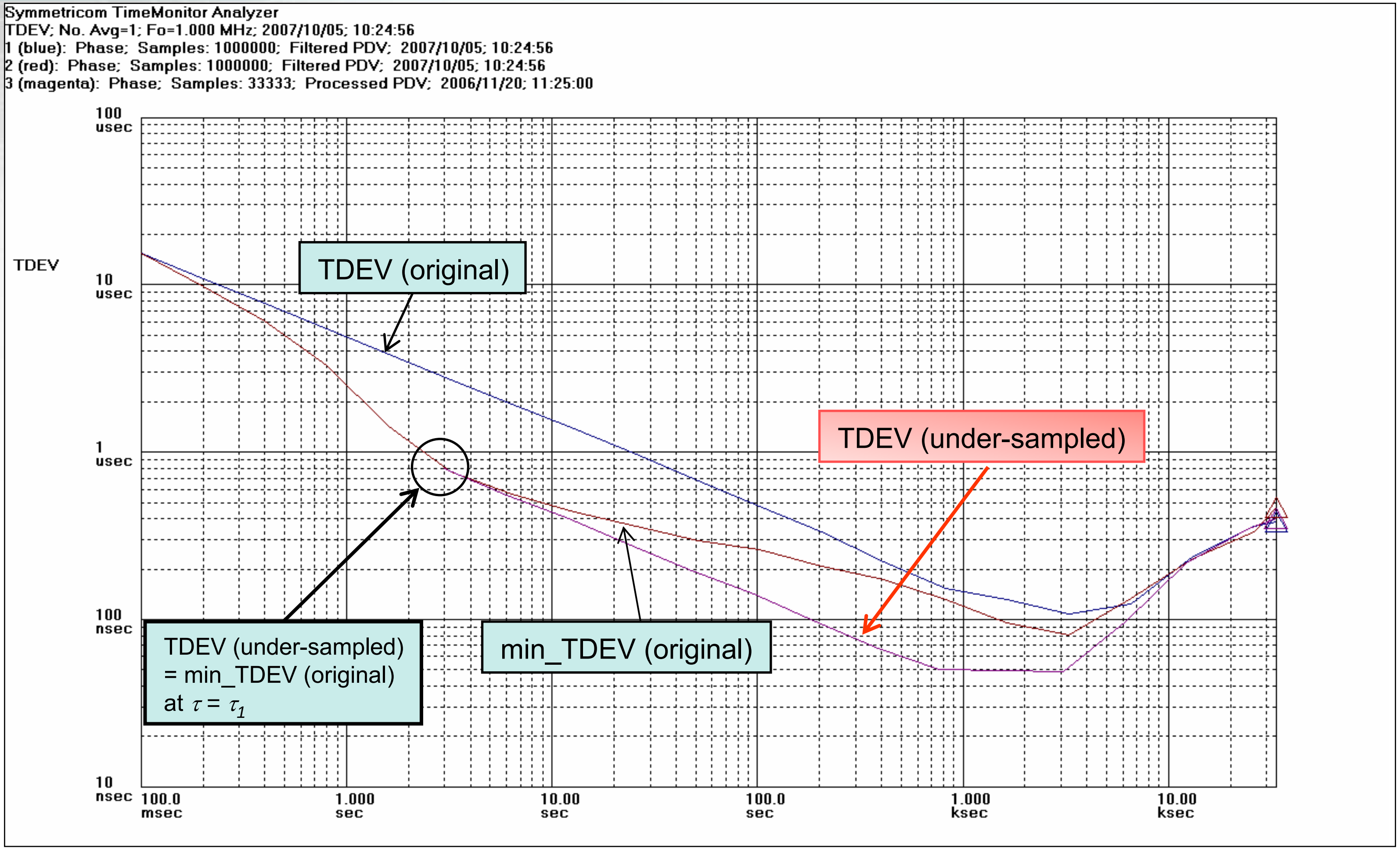
Approximations of min_TDEV



Under-sampling factor = 10

τ_0 = 100ms; τ_1 = 1000ms

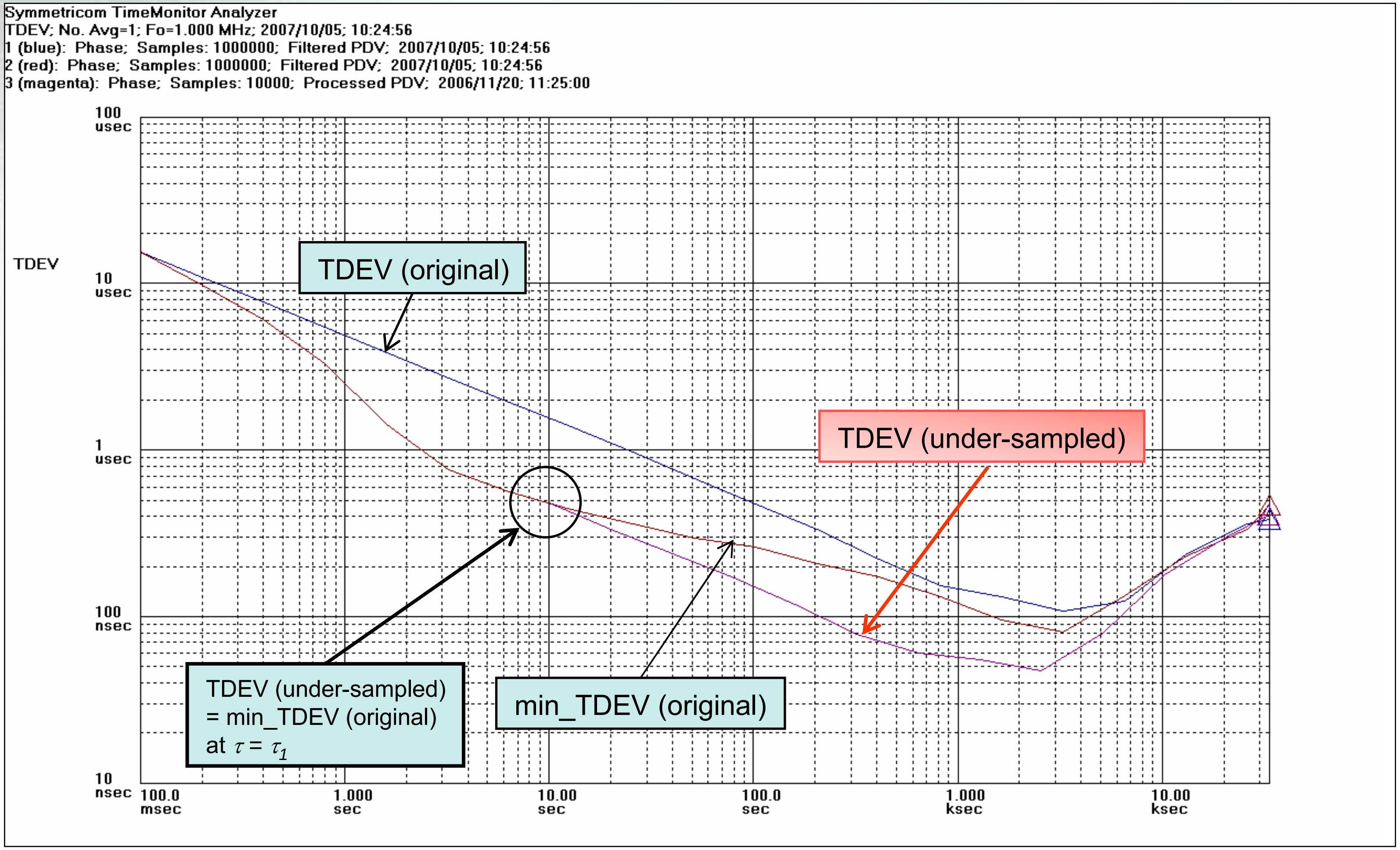
Approximations of min_TDEV



Under-sampling factor = 30

τ_0 = 100ms; τ_1 = 3000ms

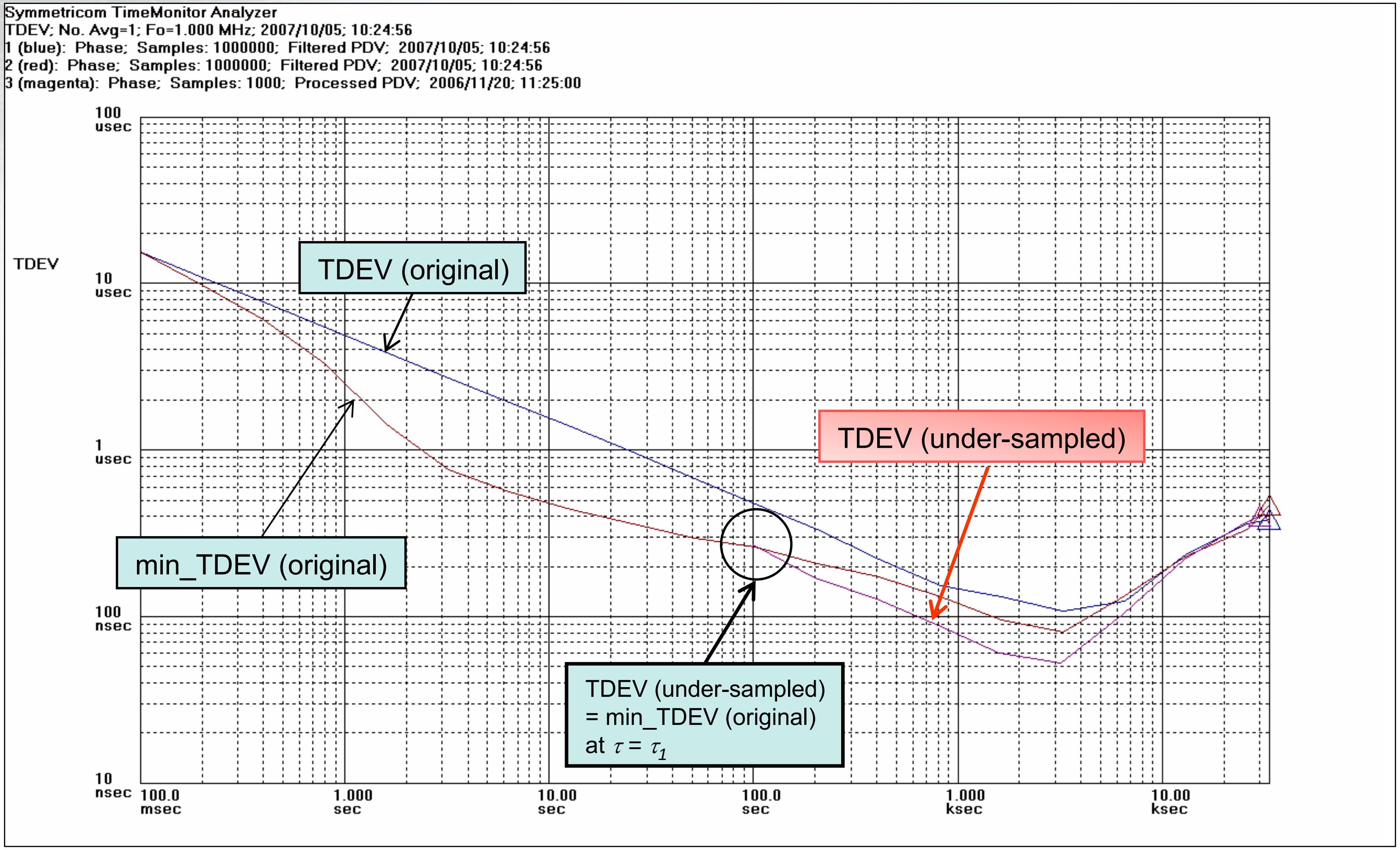
Approximations of min_TDEV



Under-sampling factor = 100

τ_0 = 100ms; τ_1 = 10000ms

Approximations of min_TDEV



Under-sampling factor = 1000

τ_0 = 100ms; τ_1 = 100000ms

Concluding Remarks

- The principal detriment to transferring timing over packet networks is packet delay variation (*PDV*)
  - Packets with excessive delay variation can be discarded
- Suitability of a packet network for distribution of timing can be quantified using metrics
  - spread-separation metrics are appropriate when the selected packets are non-uniformly spaced over time
  - TDEV and min_TDEV metrics are suitable when selected packets are chosen over equal duration, contiguous, non-overlapping periods of time
- TDEV and min_TDEV (together) provide useful information on the efficacy of clock recovery methods
- Calculation of min_TDEV can be achieved by computing the TDEV of under-sampled PDV sequences based on a "minimum" criterion