New Simulation Results for dTE for an IEC/IEEE 60802 Network, with Variable Inter-message Intervals

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Introduction - 1

- References [1] and [2] contain the most recent multiple and single replication results, respectively, for dTE for an IEC/IEEE 60802 network (based on assumptions summarized in [3])
- Included in these assumptions is a new LocalClock phase noise model, based on new frequency stability data presented in [4] and summarized in [5]
- Reference [5] obtained time histories for frequency offset, frequency drift rate, and phase offset for the LocalClock entity, based on the frequency stability versus temperature data of [4] and the periodic temperature profile described in [6]
  - In the assumptions of [3], the temperature profile was modified to shorten the period
- The results in [2] assumed the grandmaster (GM) time error was zero
  - This meant that the simulated dynamic time error (dTE) also was the dTE relative to the GM (i.e., $dTE_{R(k,0)}$, where the GM node index is 0)
- Subsequently, in [1], the GM time error was assumed to be the same as that of the LocalClock entity of each PTP Relay Instance and the PTP End Instance
  - dTE_0 and $\max|dTE_{R(k,0)}|$ (relative to the GM) were computed
  - Because the sampling instants for the GM and successive PTP Instances were not necessarily the same, it was necessary to interpolate to compute $dTE_{R(k,0)}$

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- In addition, 300 multiple, independent replications of each simulation case were run to obtain the results of [1]
  - Due to the additional run time required for 300 replications and the interpolation, only 4 selected cases of [2] were run for the multiple replication cases of [1] (cases 16, 18, 22, and 27 of [2])
    - The run time was approximately 21.5 days for 101 nodes (100 hops)

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- The results of [1] indicated that it appears possible to meet the max|TE| objective of 1 μs over 64 hops, and over 100 hops if possible, if neighborRateRatio is measured over a window of size 11, with the median of the 11 values taken as the measurement, and residence time is 1 ms
  - **Note: References [1] and [2] indicate that the window size for the neighborRateRatio computation was 7; actually, it was 11 (11 had been used in some earlier simulations for measuring both neighborRateRatio using Pdelay messages and GM Rate Ratio using Sync messages**
  - **New simulations, described here, included cases using windows of size 7 and cases using windows of size 11**
  - If residence time is 4 ms, it might be possible to meet the max|TE| objective of 1 μs over 64 hops, but it is exceeded over 100 hops
  - Timestamp granularity was assumed to be 8 ns; reducing timestamp granularity to 4 ns has small impact
  - Dynamic timestamp error was assumed to be ±8 ns, each with 0.5 probability

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- max|dTE_R| results in [1] for 100 hops ranged from 784 – 815 ns for 1 ms residence time, and was 1121 ns for 4 ms residence time and 2202 ns for 10 ms residence time
- max|dTE_R| results in [1] for 64 hops ranged from 625 – 710 ns for 1 ms residence time, and was 774 ns for 4 ms residence time and 1270 ns for 10 ms residence time
- The results in [1] for 1 ms residence time appeared to have sufficient margin for cTE for 64 hops; they might have sufficient margin for cTE for 100 hops, but this must be analyzed further
- The results in [1] for 4 ms residence time might have sufficient margin for cTE for 64 hops, but this must be analyzed further

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- However, the simulations of [1] assumed that the Sync and Pdelay intervals were fixed at 0.125 s (8 Sync messages/s) and 0.03125 messages/s (32 Pdelay exchanges/s), respectively
- Actually, both IEEE Std 802.1AS-2020 and IEEE Std 1588-2019 allow the Sync and Pdelay intervals to be variable
  - Both standards specify the mean Sync interval, the allowable variation in the successive Sync intervals, and the minimum Pdelay interval
  - Note that the Sync interval variation is at the GM; downstream nodes use syncLocked mode and send Sync after the residence time has elapsed
- The question arose during the presentation and discussion of [1] of whether max|dTE| would increase appreciably if the Sync and Pdelay intervals were allowed to vary
- It was decided that new simulations, with variable Sync and Pdelay intervals, would be run
  - It was decided to initially run single-replication simulations for case 16, but with various assumptions for variable Sync and Pdelay intervals
  - This would enable comparison with the single-replication results for case 16 with fixed Sync and Pdelay intervals (using the same initial state for the pseudo-random number generator in all cases)

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- The following slides describe the specifications for variable Sync and Pdelay intervals in IEEE Std 802.1AS-2020 (and IEEE Std 1588) and the models used in the simulator
- This is followed by a summary of the assumptions for the simulation cases, and presentation of the results
  - In [2], a total of 27 cases was considered (single replications, with zero GM time error)
  - In [1], cases 16, 18, 22, and 27 of [2] were run (300 multiple replications with non-zero GM time error)
  - In the current presentation, all the cases are based on case 16 of [2], but Sync and Pdelay intervals are allowed to vary

Model for Variable Sync Interval - 1

- IEEE Std 802.1AS-2020 requires in 10.7.2.3 (an analogous requirement is in 9.5.9.2 of IEEE Std 1588-2019):

When the value of syncLocked is FALSE, time-synchronization messages shall be transmitted such that the value of the arithmetic mean of the intervals, in seconds, between message transmissions is within ± 30% of $2^{currentLogSyncInterval}$. In addition, a PTP Port shall transmit time-synchronization messages such that at least 90% of the inter-message intervals are within ± 30% of the value of $2^{currentLogSyncInterval}$. The interval between successive time-synchronization messages should not exceed twice the value of $2^{portDS.logSyncInterval}$ in order to prevent causing a syncReceiptTimeout event. The PortSyncSyncSend state machine (see 10.2.12) is consistent with these requirements, i.e., the requirements here and the requirements of the PortSyncSyncSend state machine can be met simultaneously.

NOTE 1—A minimum number of inter-message intervals is necessary in order to verify that a PTP Port meets these requirements. The arithmetic mean is the sum of the inter-message interval samples divided by the number of samples. For more detailed discussion of statistical analyses, see Papoulis [B25].

Model for Variable Sync Interval – 2

- The above requirements do not specify the actual probability distribution; however, it was decided to model the Sync Intervals as being gamma-distributed
  - The gamma distribution is often used to model inter-message times in networks
  - The same model was used in simulations for the PTP Telecom Time Profile with full timing support from the network (ITU-T Rec. G.8275.1), see 11.2 and Eqs. (11-1) through (11-10) of [7])
- While both 802.1AS-2020 and 1588-2019 both allow variation in the duration of the Sync intervals up to $\pm$ 30% of the mean Sync interval, it was decided in the discussion of [1] to consider variations of $\pm\beta$, with β = 10%, 20%, and 30% (i.e., three cases)
- The shape and scale parameters of the gamma distribution will be chosen such that the distribution has the desired mean and that 90% of the probability mass is within β of the mean

Model for Variable Sync Interval – 3

The gamma probability density function is:

$$p_X(x;\lambda,a) = \frac{\lambda(\lambda x)^{a-1} e^{-\lambda x}}{\Gamma(a)}$$

Here, X is the random variable, i.e., the Sync interval, x is the value of the random variable, λ is the scale parameter, a is the shape parameter, and $\Gamma(\cdot)$ is the gamma function

$$\Gamma(a) = \int_0^\infty x^{a-1} e^{-x} dx$$

Note that $\Gamma(a+1) = a\Gamma(a)$ and $\Gamma(a) = (a\text{-}1)!$. The mean and variance of the gamma distribution, μ and σ^2, are related to λ and *a* by

$$\mu = \frac{a}{\lambda} \qquad \sigma^2 = \frac{a}{\lambda^2}$$

$$\lambda = \frac{\mu}{\sigma^2} \qquad a = \frac{\mu^2}{\sigma^2}$$

Model for Variable Sync Interval – 4

The condition that the inter-message interval must be within β of the mean with 90% probability, where now β is a fraction (0.1, 0.2, or 0.3) can be written

$$\int_{(1-\beta)\mu}^{(1+\beta)\mu} \frac{\lambda(\lambda x)^{a-1} e^{-\lambda x}}{\Gamma(a)} dx = 0.9$$

Making the change of variable $u = \lambda x$, the above can be written

$$\int_{(1-\beta)\lambda\mu}^{(1+\beta)\lambda\mu} \frac{u^{a-1} e^{-u}}{\Gamma(a)} du = 0.9$$

From the equation for the mean, μ, on the previous slide, the shape parameter a is given by $a = \lambda\mu$. Then the above equation can be written

$$\int_{(1-\beta)a}^{(1+\beta)a} \frac{u^{a-1} e^{-u}}{\Gamma(a)} du = 0.9$$

Model for Variable Sync Interval – 5

The incomplete gamma function, $P(a, x)$, is defined as (see 6.5 of [8])

$$P(a,x) = \int_0^x \frac{u^{a-1}e^{-u}}{\Gamma(a)}du$$

In addition, the incomplete gamma function is related to the Chi-Square distribution by

$$P(a,x) = \mathrm{P}(\chi^2|\nu)$$

with $\nu = 2a$ and $\chi^2 = 2x$, and the Chi-Square distribution is given by

$$P(\chi^2|\nu) = \frac{1}{\left[2^{\nu/2}\Gamma(\nu/2)\right]}\int_0^{\chi^2} u^{(\nu/2)-1}e^{-u/2}\ du$$

Then the last equation on slide 11 can be written

$$P([1+\beta]a,a) - P([1-\beta]a,a) = P(2[1+\beta]a\,|\,2a) - P(2[1-\beta]a\,|\,2a) = 0.9$$

Model for Variable Sync Interval - 6

The Chi-Square distribution was introduced only because some references tabulate (and some calculators or apps compute) the Chi-Square distribution rather than the incomplete gamma function; they simply refer to the Chi-Square distribution for values of the incomplete gamma function.

The values of the shape parameter a corresponding to $\beta = 0.2$, and 0.3 were determined by trial and error search using an HP 48GX calculator (this calculator can determine values of the Chi-Square distribution), and then checked using the incomplete gamma function App available at https://keisan.casio.com/exec/system/1180573447 . The value of a corresponding to $\beta = 0.1$ required computation of the Chi-Square distribution that exceeded the maximum floating point number that could be represented by the calculator (10^{500}); however, the App at the above link was able to perform the computations. The results are given on the next slide

Model for Variable Sync Interval - 7

- Values of the gamma distribution shape parameter corresponding to β values of 0.1, 0.2, and 0.3 (i.e., 90% of the Sync intervals within the fraction $\pm\beta$ of the mean Sync interval

Fraction β	Shape Parameter a
0.1	270.5532
0.2	66.960
0.3	29.374

- Note that for smaller values of β, the required shape parameter is larger. The computations of the incomplete gamma function (or the Chi-Square distribution) require computing numbers on the order of $\Gamma(a) = (a\text{-}1)!$. For $\beta = 0.1$, the computation of $270!$ is larger then the largest value that can be handled by the HP 48GX (but is within the capabilities of the App whose link is given on the previous slide).

Model for Variable Sync Interval - 8

- Gamma-distributed samples are generated by first generating a uniformly-distributed pseudo-random value, u, in the range [0,1]
- A gamma-distributed pseudo-random sample, x, is obtained using the transformation

$$x = F^{-1}(u;\lambda,a)$$

where $F^{-1}(u;\lambda,a)$ is the inverse of the cumulative gamma distribution with shape parameter λ and scale parameter *a*

- This requires evaluation of the inverse of the incomplete gamma function, which is done by successively evaluating the incomplete gamma function and using binary search with a fractional change threshold for one iteration of 2.5×10^{-8}
- The evaluation of the incomplete gamma function in the simulator makes use of the series expansion in 6.5.29 of [8] and the built-in log gamma function provided by Linux (while this also could have been used in determining values of a, the tools described previously were more convenient)

Model for Variable Pdelay Interval - 1

- IEEE Std 802.1AS-2020 has the following NOTE in 11.5.2.2 (it refers to the requirement in 9.5.13.2 of IEEE Std 1588-2019):

NOTE 3—The MDPdelayReq state machine ensures that the times between transmission of successive Pdelay_Req messages, in seconds, are not smaller than $2^{currentLogPdelayReqInterval}$. This is consistent with IEEE Std 1588-2019, which requires that the logarithm to the base 2 of the mean value of the interval, in seconds, between Pdelay_Req message transmissions is no smaller than the interval computed from the value of the portDS.logMinPdelayReqInterval member of the data set of the transmitting PTP Instance. The sending of Pdelay_Req messages is governed by the LocalClock and not the synchronized time (i.e., the estimate of the Grandmaster Clock time). Since the LocalClock frequency can be slightly larger than the Grandmaster Clock frequency (e.g., by 100 ppm, which is the specified frequency accuracy of the LocalClock; see B.1.1), it is possible for the time intervals between successive Pdelay_Req messages to be slightly less than $2^{currentLogPdelayReqInterval}$ when measured relative to the synchronized time.

- However, the actual requirement in 9.5.13.2 of IEEE 1588 is:

Subsequent Pdelay_Req messages shall be transmitted such that the value of the arithmetic mean of the intervals, in seconds, between Pdelay_Req message transmissions is not less than the value of $0.9 \times 2^{portDS.logMinPdelayReqInterval}$.

- This requirement will be satisfied even if the LocalClock is 100 ppm fast due to the factor of 0.9

Model for Variable Pdelay Interval - 2

- IEEE 802.1AS and IEEE 1588-2019 do not specify the distribution for the Pdelay interval, nor do they specify the maximum amount that the actual intervals can exceed $2^{\text{portDS.logMinPdelayReqInterval}}$
- For the simulations, it was decided to use a uniform distribution over the range $[P, 1.3P]$, where P is $2^{\text{portDS.logMinPdelayReqInterval}}$
  - i.e., the successive Pdelay intervals vary randomly between the specified value (i.e. 0.03125 s for the simulation cases here) and a value 30% larger (i.e., 0.040625 s for the simulation cases here)
- However, to see whether the effect of allowing the Pdelay interval to vary is appreciable, the cases with each of the above values for β for Sync interval variation will be run with both no Pdelay interval variation and 30% Pdelay Interval variation

Assumptions for Temperature Profile (from [3])

- The temperature history is assumed to vary between – 40°C and +85°C, at a rate of 1°C /s
- When the temperature is increasing and reaches +85°C, it remains at +85°C for 30 s
- The temperature then decreases from +85°C to – 40°C at a rate of 1°C /s; this takes 125 s
- The temperature then remains at – 40°C for 30 s
- The temperature then increases to +85°C at a rate of 1°C /s; this takes 125 s
- The duration of the entire cycle (i.e., the period) is therefore 310 s (5.166667 min)

Assumptions for Frequency Stability due to Temperature Variation

- The dependence of frequency offset on temperature is assumed to be as described in [4] and [5]
  - Specifically, the values a_0, a_1, a_2, and a_3 computed in [4] will be used in the cubic polynomial fit, and the resulting frequency offset will be multiplied by 1.1 (i.e., a margin of 10% will be used).
- The frequency stability data that this polynomial fit is based on is contained in the Excel spreadsheet attached to [5]
  - This data was provided by the author of Reference [4]
- The time variation of frequency offset will be obtained from the cubic polynomial frequency dependence on temperature, and the temperature dependence on time described in the previous slide
  - The time variation of phase/time error at the LocalClock entity will be obtained by integrating the above frequency versus time waveform
  - The time variation of frequency drift rate at the LocalClock entity will be obtained by differentiating the above frequency versus time waveform

- In previous simulations (see [1] and [2]), two types of assumptions are used for relative time offsets of the phase error histories at each node:
  - a) Choose the phase of the LocalClock time error waveform at each node randomly in the range [0,T], at initialization, where T is the period of the phase and frequency variation waveforms (i.e., 310 s, see slide 4)
  - b) Choose the phase of the LocalClock time error waveform at each node randomly in the range [0, 0.1T], at initialization, where T is the period of the phase and frequency variation waveforms (i.e., 310 s, see slide 4)
    - A uniform probability distribution is used for the random choice
    - 0.1T = 31 s, i.e., any periodic LocalClock time error waveform will be offset from any other such waveform by at most 31 s
- In the simulations here (based on case 16 of [1] and [2]), (a) is used

Other Assumptions - 1

- Additional assumptions
  - Mean Sync interval: 125 ms
  - Mean Pdelay interval: 31.25 ms
  - Timestamp granularity: 8 ns
  - Residence time: 1 ms
  - Timestamp error (±8 ns, each with 0.5 probability)
- Other assumptions are taken from [9], and are summarized on the following slides

Other Assumptions - 2

Assumption/Parameter	Description/Value
Hypothetical Reference Model (HRM), see note following the tables	101 PTP Instances (100 hops; GM, followed by 99 PTP Relay Instances, followed by PTP End Instance
Computed performance results	(a) $\max\lvert dTE_{R(k,\,0)}\rvert$ (i.e., maximum absolute relative time error between node k ($k > 0$) and GM (b) Measured LocalClock rateRatio (frequency offset) relative to GM, for comparison with actual LocalClock frequency offset (results will be plotted for nodes 2, 35, 68, and 101 (where node 2 is the first node after the GM, and the GM is node 1; note that in [3], the GM was node 0, and the above nodes were 1, 34, 67, and 100))
Use syncLocked mode for PTP Instances downstream of GM	Yes
Endpoint filter parameters	$K_pK_o = 11$, $K_iK_o = 65$ ($f_{3dB} = 2.5998$ Hz, 1.288 dB gain peaking, $\zeta = 0.68219$)
Simulation time	3150 s; discard first 50 s to eliminate any startup transient before computing $\max\lvert dTE_{R(k,\,0)}\rvert$ (i.e., 10 cycles of frequency variation after discard)

Other Assumptions - 3

Assumption/Parameter	Description/Value
Number of independent replications, for each simulation case	300
GM rateRatio and neighborRateRatio computation granularity	0
Mean link delay	500 ns
Link asymmetry	0
Dynamic timestamp error for event messages (Sync, Pdelay-Req, Pdelay_Resp) due to variable delays within the PHY	±8 ns; for each timestamp taken, a random error is generated. The error is + 8 ns with probability 0.5, and – 8 ns with probability 0.5. The errors are independent for different timestamps and different PTP Instances.
Any variable PHY delay in addition to the dynamic timestamp error described above is assumed to be zero	0

Other Assumptions - 4

- neighborRateRatio was computed using windows of size of 7 and of size 11 (i.e., both cases were simulated)
  - The difference was taken between respective timestamps of current Pdelay exchange and 7^{th} or 11^{th} previous Pdelay exchange
  - In addition, the current estimate of neighborRateRatio was taken as the median of the most recent 7 or 11 measurements (including the current measurement)
- A total of 12 subcases of case16 (of [1] and [2]) were simulated
  - (3 values for Sync Interval variation) × (2 values for Pdelay Interval variation) × (2 values for window size for neighborRateRatio computation)
- For convenience, cases 16 – 27 of [1] and [2] are summarized on the following slides, though of these, only cases based on case 16 were simulated for the results here
  - The cases here use the same numbering as in [2]; however, cases 1 – 15 of [2] are not of interest here (these cases did not use a window, with median, for computing neighborRateRatio)
- The 12 subcases of case 16 simulated here are summarized on the slide that follows the next slide

Summary of Simulation Cases (highlighted case was the one whose subcases were simulated)

Case	Residence time (ms)	Timestamp gran (ns)	Fract of cycle over which initial time error waveforms are randomized (%)	Compute neighborRateRatio averaging over window of size 7 and taking median
16	1	8	100	Yes
17	1	4	100	Yes
18	4	8	100	Yes
19	4	4	100	Yes
20	10	8	100	Yes
21	10	4	100	Yes
22	1	8	10	Yes
23	1	4	10	Yes
24	4	8	10	Yes
25	4	4	10	Yes
26	10	8	10	Yes
27	10	4	10	Yes

Summary of Subcases of Case 16 Simulated

Subcase	Sync Interval variation (%)	Pdelay Interval variation (%)	Window Size for neighborRateRatio measurement
1	10	0	11
2	20	0	11
3	30	0	11
4	10	30	11
5	20	30	11
6	30	30	11
7	10	0	7
8	20	0	7
9	30	0	7
10	10	30	7
11	20	30	7
12	30	30	7

max|dTE_R| Results - 1

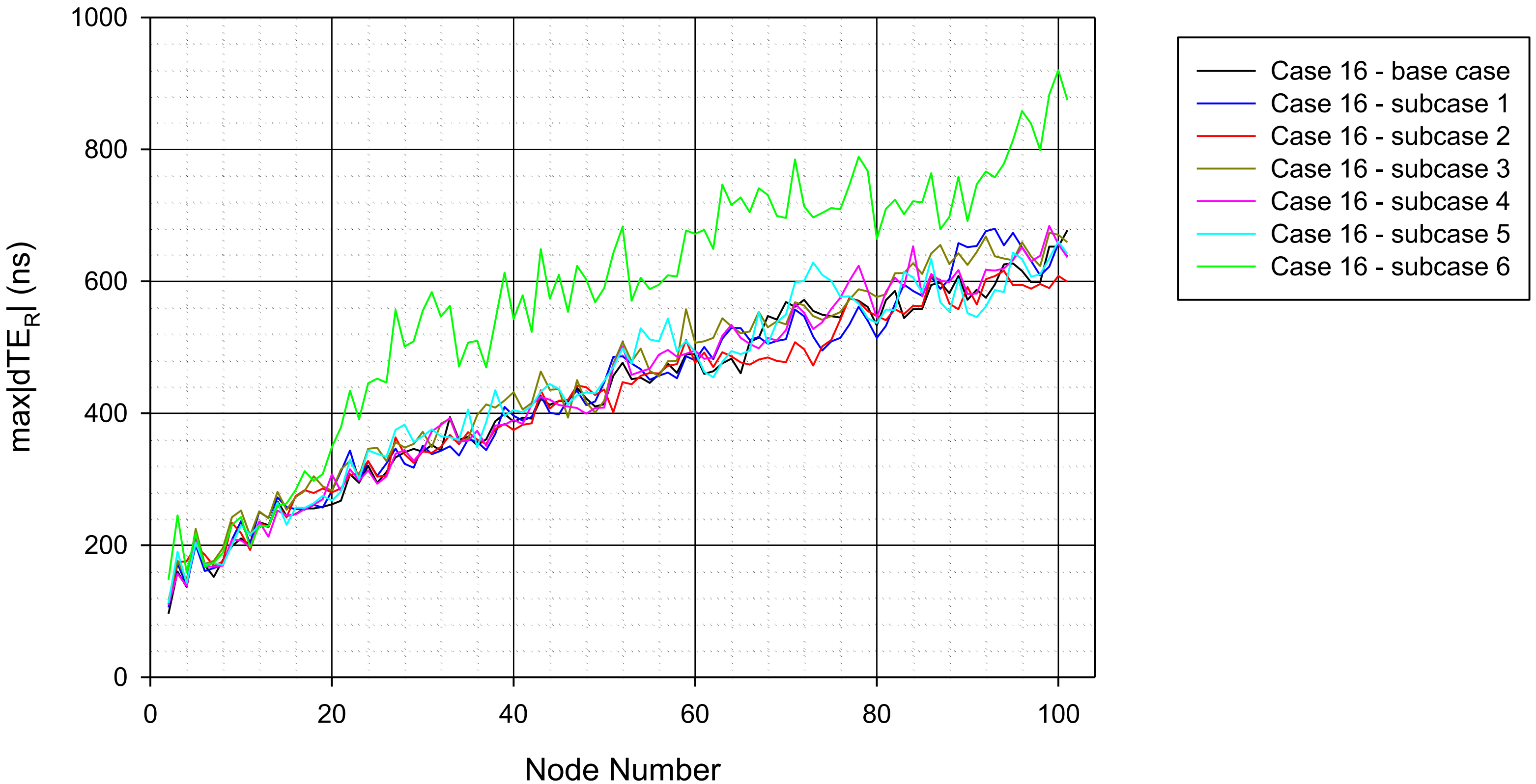
- Results for max|dTE_R|, relative to the GM, versus node number are summarized on the next two slides, for case 16, subcases 1 – 6 (first slide) and subcases 7 – 12 (second slide)
  - For comparison, the single-replication max|dTE_R| results from replication 1 of [1] are also shown on each slide (window of size 11, no variation of Sync or Pdelay intervals, GM time error modeled)
  - The single-replication results from replication 1 of [1] (the base case) are used rather than multiple replication results from [1] because the new results are for single replications
    - Multiple replication results will almost always be larger than single-replication results, for the same case/subcase

max|dTE_R| Results - 2

- Following the max|dTE_R| plots, detailed time history results for each of subcases 3, 6, and 12, for nodes 2, 35, 68, and 101 (GM is node 1), are given:
  - These subcases all have 30% Sync interval variation, which is the largest Sync interval variation considered
  - Subcases 3 and 6 have window of size 11, while subcase 12 has window of size 7
  - Subcase 3 has no Pdelay interval variation, while subcases 6 and 12 have 30% Pdelay interval variation
  - Due to the potentially large number of plots, detailed time history results are not presented for every node of every case; however, results for additional nodes and cases can be supplied if desired

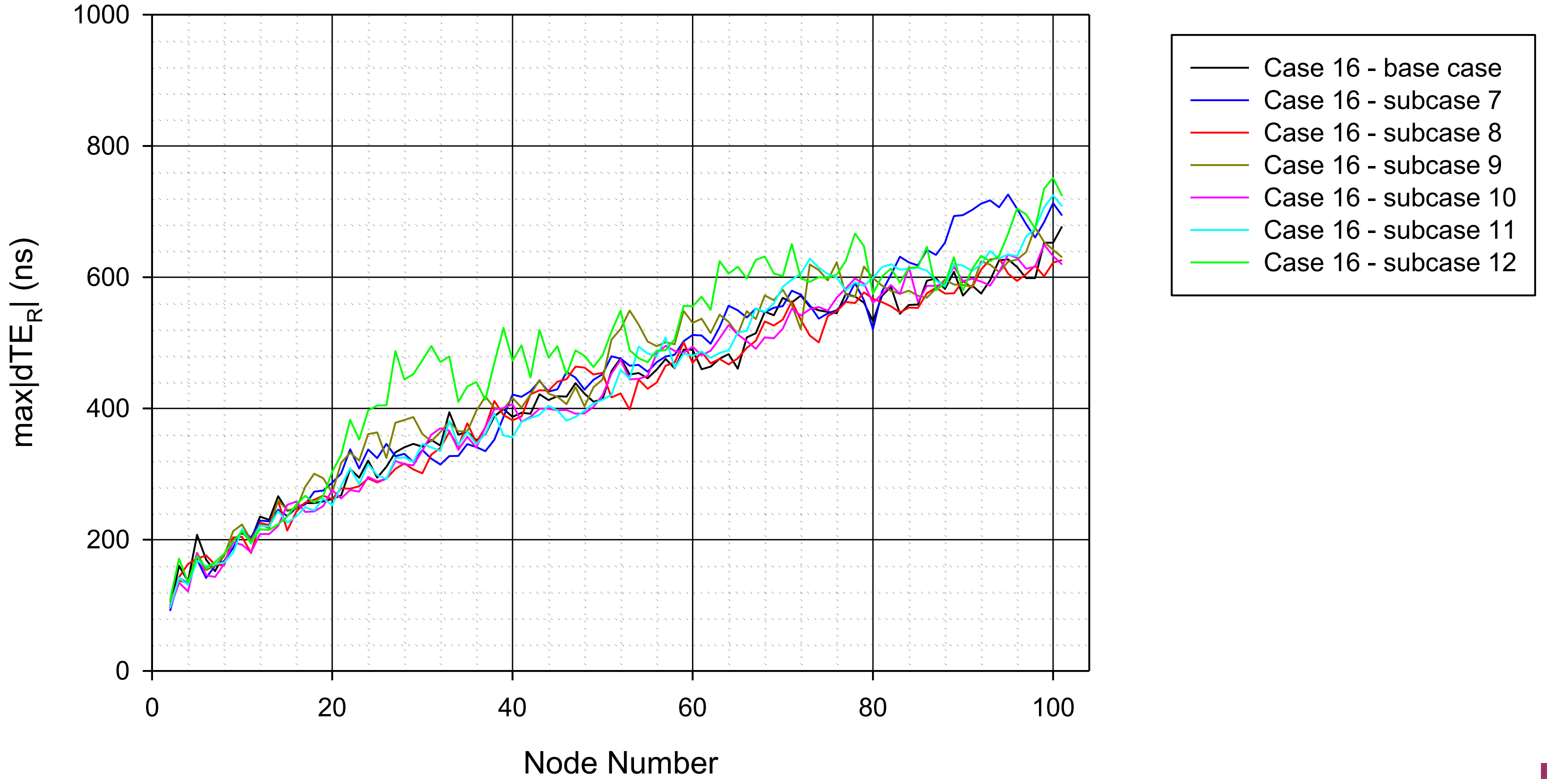
max|dTE$_R$| Results - 3

Case 16 - single replication results
Window size 11
Base case: no Sync or Pdelay interval variation
Subcases 1-3: Sync var (+/- 10, 20, 30%)
Subcases 4-6: Sync (+/- 10, 20, 30%) and Pdelay var (0-30%)
GM time error modeled
GM labeled node 1
Clock Model (all clocks): Frequency vs temperature stability and temperature vs time profile from [2]
Accumulate neighborRateRatio, which is measured with window of size 7 and median
KpKo = 11, KiKo = 65 (f3dB = 2.6 Hz, gain pk = 1.288 dB, zeta = 0.68219)



max|dTE_R| Results - 4

Case 16 - single replication results
Window size 7
Base case: no Sync or Pdelay interval variation
Subcases 7-9: Sync var (+/- 10, 20, 30%)
Subcases 10-12: Sync (+/- 10, 20, 30%) and Pdelay var (0-30%)
GM time error modeled
GM labeled node 1
Clock Model (all clocks): Frequency vs temperature stability and temperature vs time profile from [2]
Accumulate neighborRateRatio, which is measured with window of size 7 and median
KpKo = 11, KiKo = 65 (f3dB = 2.6 Hz, gain pk = 1.288 dB, zeta = 0.68219)



max|dTE_R| Results - 3

Subcase	max|dTE_R|, 64 hops (ns)	max|dTE_R|, 100 hops (ns)
Base case	460	677
1	529	637
2	477	599
3	521	659
4	514	636
5	490	642
6	727	875
7	549	694
8	476	626
9	513	630
10	513	619
11	515	708
12	616	724

64 hops results are for node 65

100 hops results are for node 101

Base case is case 16 of [1], replication 1

Discussion of max|dTE_R| Results - 1

- The results for 64 hops range from 477 ns (case 2) to 727 ns (case 6), and all of them exceed the base case result of 460 ns
- The results for 100 hops range from 599 ns (case 2) to 875 ns (case6); 8 of the cases have results that are less than the base case result of 677 ns
- Case 6, which has 30% variation for both Sync and Pdelay intervals and uses a window of size 11, is the worst case (this is clearly indicated in the plot showing subcases 1 – 6)
  - This is likely because the larger variation in the Pdelay interval and the larger window size results in a less accurate neighborRateRatio measurement, and larger Sync intervals for some Sync messages results in greater time error
- It is difficult to discern trends from the results due to their statistical variability
  - Other than the fact that case 6 has larger max|dTE_R| than the other cases, and that in general the variability of the Sync and Pdelay intervals results in larger max|dTE_R|, general trends are not evident
  - The plots of the multiple replication results in [1] (slides 14 and 15 of [1]) are much smoother)

Discussion of max|dTE_R| Results - 1

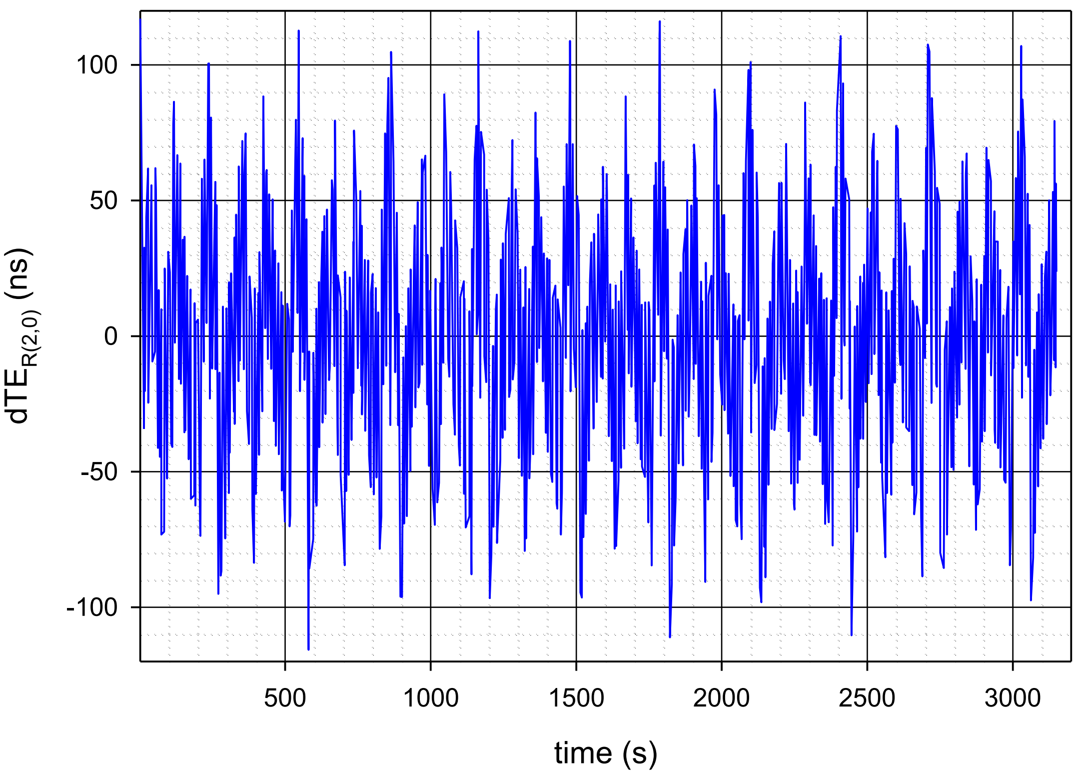
- In particular, it is not clear whether, in general, a window of size 7 gives better or worse results than a window of size 11
  - While the larger window averages (filters) more of the variability in the neighborRateRatio measurement, which improves the estimate, the actual frequency offset changes more during the duration of the larger window, which makes the estimate worse
- It appears possible to meet the 1 μs objective over 64 hops, and over 100 hops if possible, but subject to the margin needed for cTE
  - Note that the results will increase when multiple replications of the simulations are run; the increase could be as much as 100 – 250 ns
    - This was observed previously for case 16, where the multiple replication results were 710 ns and 815 ns for nodes 64 and 100, respectively (see slide 20 of [1]), and the single replication results were 460 ns and 677 ns, respectively (see the base case in slide 31 above, which is for replication 1 but with GM time error modeled)

Detailed Results

- In the detailed results that follow, the following required interpolation, to compute values relative to the GM (node 1):
  - max|dTE_R| (plot 1 for each node of each case)
  - Actual frequency of the LocalClock entity relative to the GM (2nd curve of plot 2 for each node of each case)
  - Difference between actual frequency of the LocalClock entity relative to the GM and the measured difference (plot 3 for each node of each case)
  - Interpolation was not needed for the measured difference (i.e., measured GM rateRatio) between the LocalClock entity relative to the GM
- Note that plots of interpolated results have fewer data points
  - Therefore, these plots appear more sparse
- For frequency results, only the first 500 s is plotted (with the first 10 s omitted to eliminate any startup transient) so that the overall detailed periodic behavior can be seen more readily
- Note that the frequency results are frequency offsets of each node relative to the GM; therefore, each waveform is the difference between the LocalClock waveform and version of it shifted by a random amount (since the GM time error is the same as that of each subsequent PTP Instance)

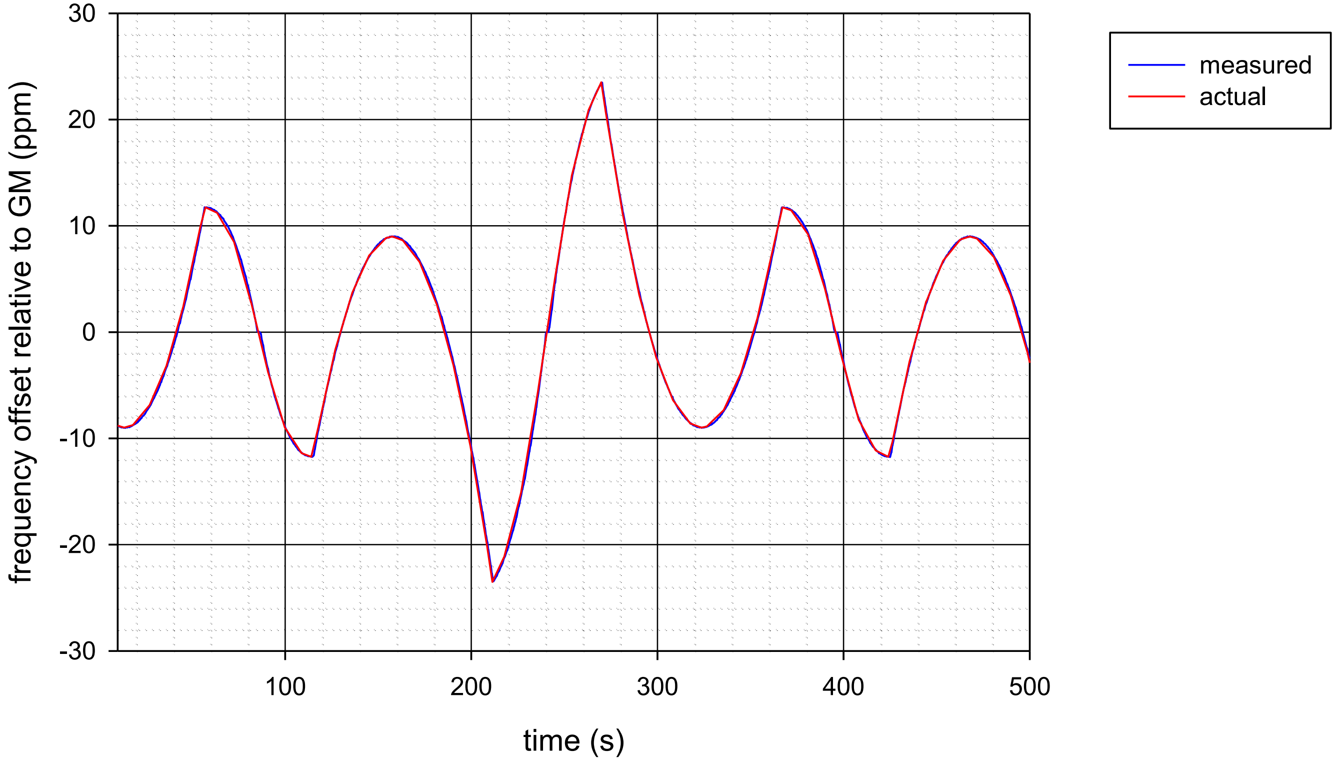
Case16, Subcase 3, Node 2 Detailed Results – 1

Subcase 3, Node 2
Replication 1: 2 - 3150 s
GM time error modeled
Clock Model (all clocks): Frequency vs temperature stability and temperature vs time profile from [3]
Accumulate neighborRateRatio, which is measured with window of size 11 and median
KpKo = 11, KiKo = 65 (f3dB = 2.6 Hz, gain pk = 1.288 dB, zeta = 0.68219)
Initial LocalClock phase waveforms chosen randomly over 100% of cycle
Residence time: 1 ms
Timestamp granularity: 8 ns
30% variation for Sync, 0% for Pdelay Intervals



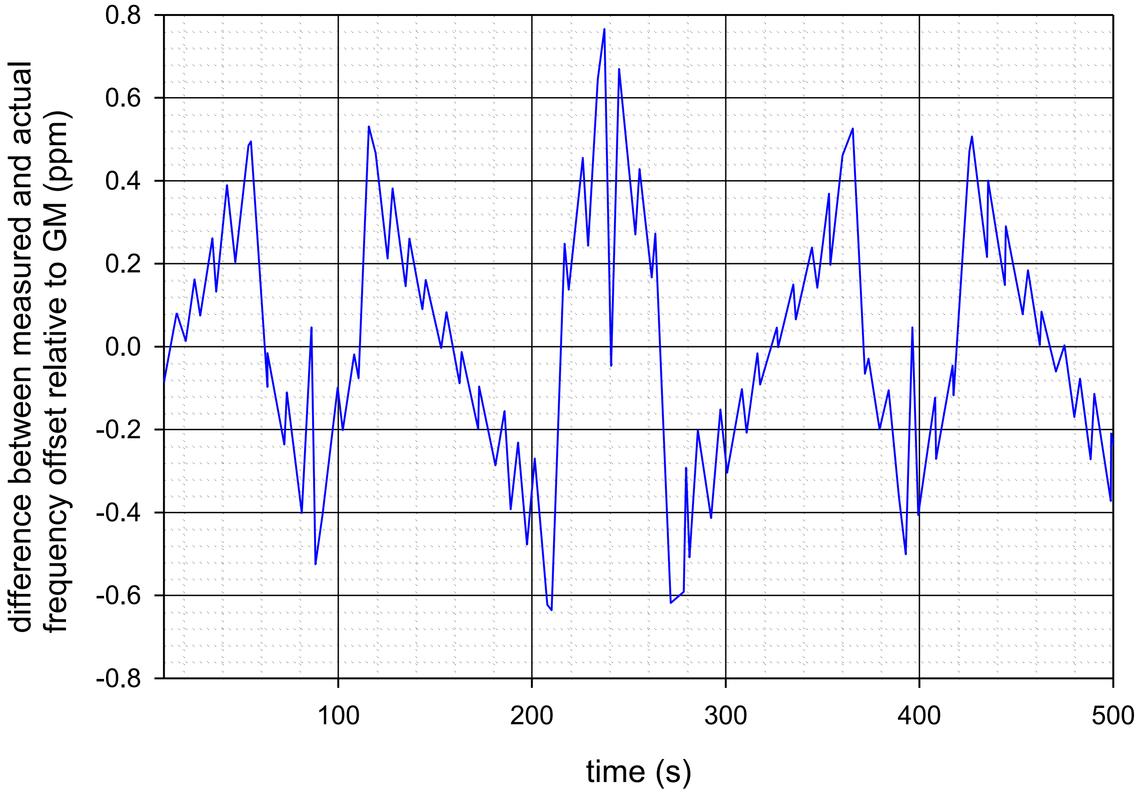
Case16, Subcase 3, Node 2 Detailed Results – 2

Subcase 3, Node 2
Replication 1: 2 - 3150 s
GM time error modeled
Clock Model (all clocks): Frequency vs temperature stability and temperature vs time profile from [3]
Accumulate neighborRateRatio, which is measured with window of size 11 and median
KpKo = 11, KiKo = 65 (f3dB = 2.6 Hz, gain pk = 1.288 dB, zeta = 0.68219)
Initial LocalClock phase waveforms chosen randomly over 100% of cycle
Residence time: 1 ms
Timestamp granularity: 8 ns
30% variation for Sync, 0% for Pdelay Intervals



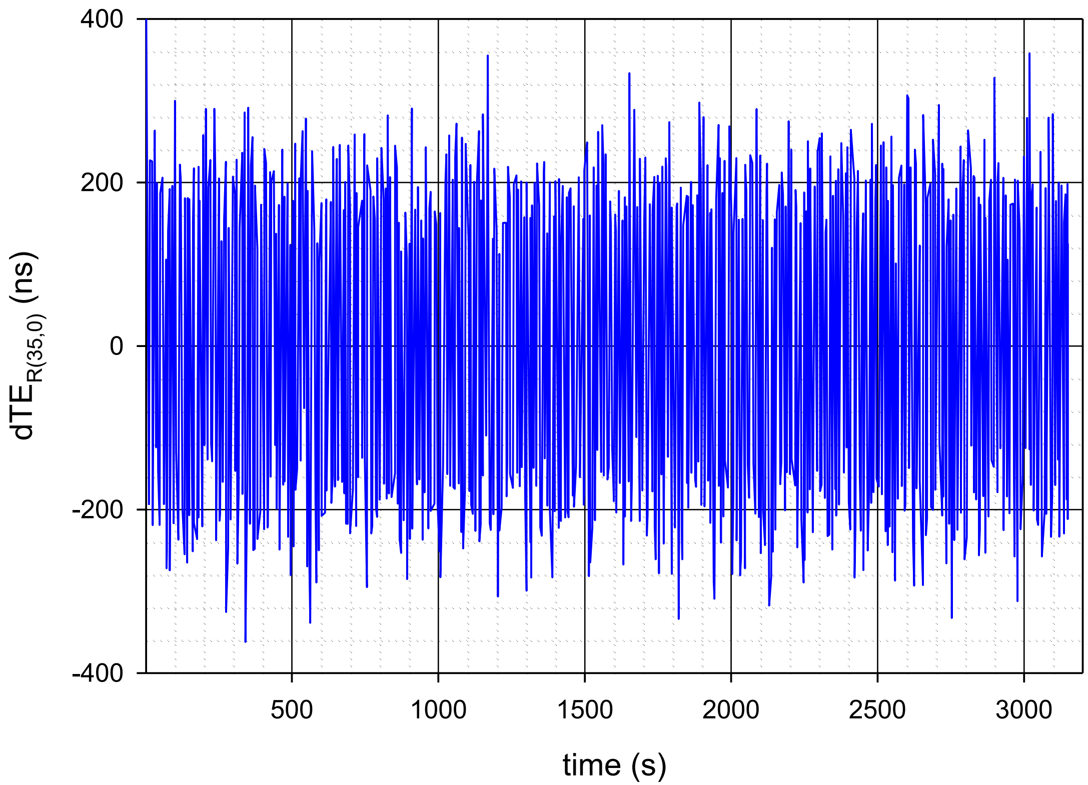
Case16, Subcase 3, Node 2 Detailed Results – 3

Subcase 3, Node 2
Replication 1: 2 - 3150 s
GM time error modeled
Clock Model (all clocks): Frequency vs temperature stability and temperature vs time profile from [3]
Accumulate neighborRateRatio, which is measured with window of size 11 and median
KpKo = 11, KiKo = 65 (f3dB = 2.6 Hz, gain pk = 1.288 dB, zeta = 0.68219)
Initial LocalClock phase waveforms chosen randomly over 100% of cycle
Residence time: 1 ms
Timestamp granularity: 8 ns
30% variation for Sync, 0% for Pdelay Intervals



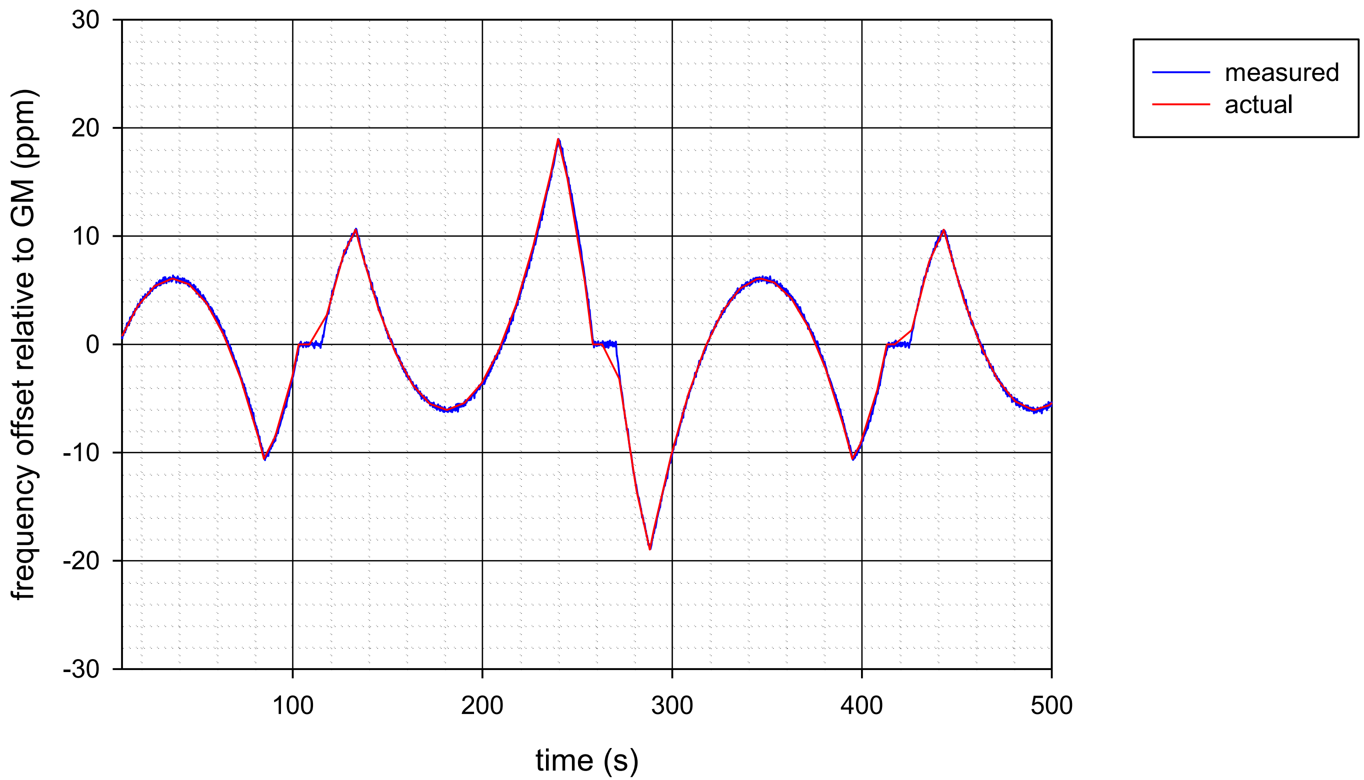
Case16, Subcase 3, Node 35 Detailed Results - 1

Subcase 3, Node 35
Replication 1: 2 - 3150 s
GM time error modeled
Clock Model (all clocks): Frequency vs temperature stability and temperature vs time profile from [3]
Accumulate neighborRateRatio, which is measured with window of size 11 and median
KpKo = 11, KiKo = 65 (f3dB = 2.6 Hz, gain pk = 1.288 dB, zeta = 0.68219)
Initial LocalClock phase waveforms chosen randomly over 100% of cycle
Residence time: 1 ms
Timestamp granularity: 8 ns
30% variation for Sync, 0% for Pdelay Intervals



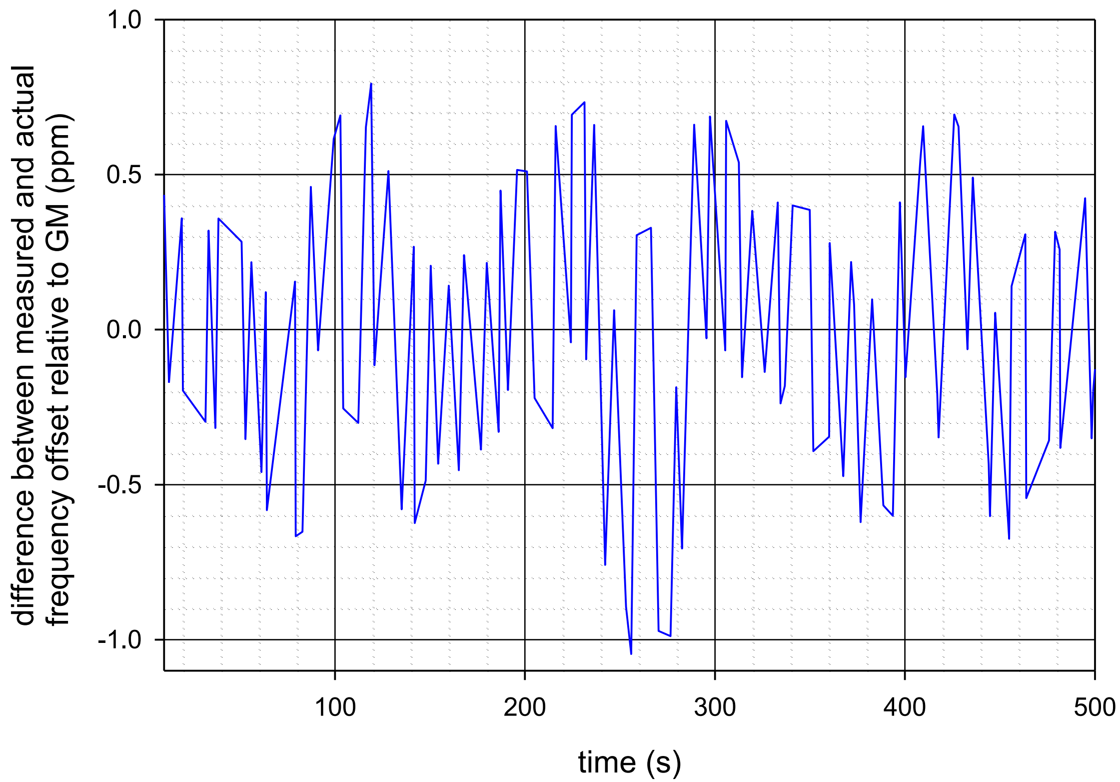
Case16, Subcase 3, Node 35 Detailed Results - 2

Subcase 3, Node 35
Replication 1: 2 - 3150 s
GM time error modeled
Clock Model (all clocks): Frequency vs temperature stability and temperature vs time profile from [3]
Accumulate neighborRateRatio, which is measured with window of size 11 and median
KpKo = 11, KiKo = 65 (f3dB = 2.6 Hz, gain pk = 1.288 dB, zeta = 0.68219)
Initial LocalClock phase waveforms chosen randomly over 100% of cycle
Residence time: 1 ms
Timestamp granularity: 8 ns
30% variation for Sync, 0% for Pdelay Intervals



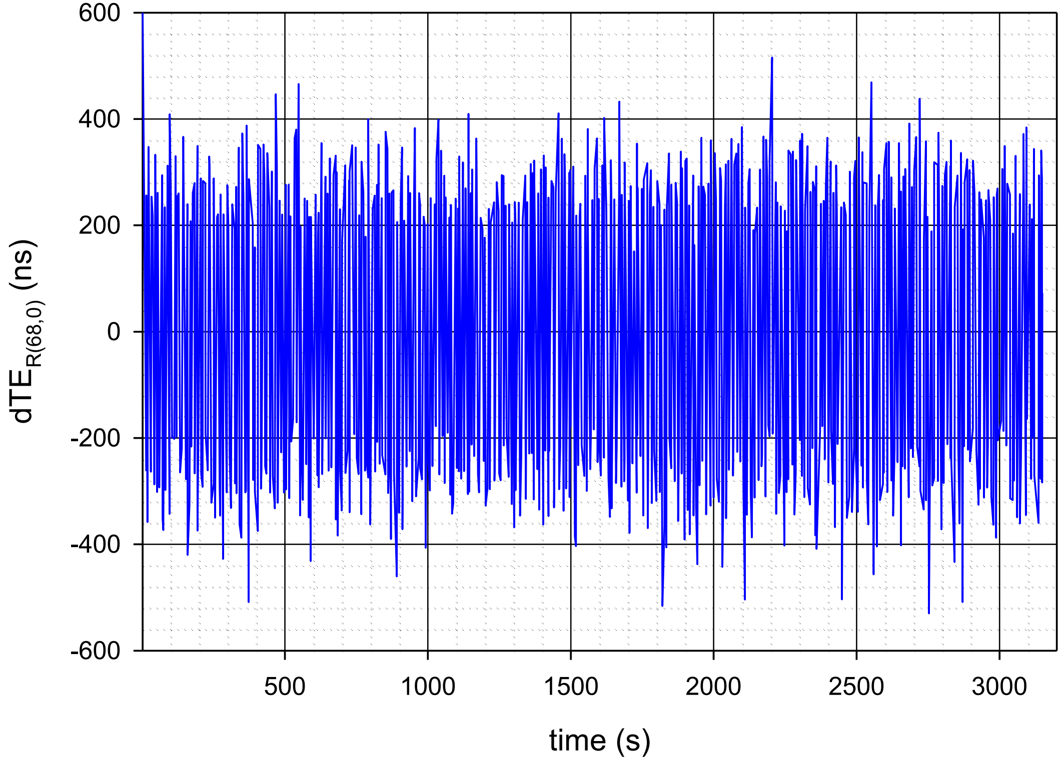
Case16, Subcase 3, Node 35 Detailed Results - 3

Subcase 3, Node 35
Replication 1: 2 - 3150 s
GM time error modeled
Clock Model (all clocks): Frequency vs temperature stability and temperature vs time profile from [3]
Accumulate neighborRateRatio, which is measured with window of size 11 and median
KpKo = 11, KiKo = 65 (f3dB = 2.6 Hz, gain pk = 1.288 dB, zeta = 0.68219)
Initial LocalClock phase waveforms chosen randomly over 100% of cycle
Residence time: 1 ms
Timestamp granularity: 8 ns
30% variation for Sync, 0% for Pdelay Intervals



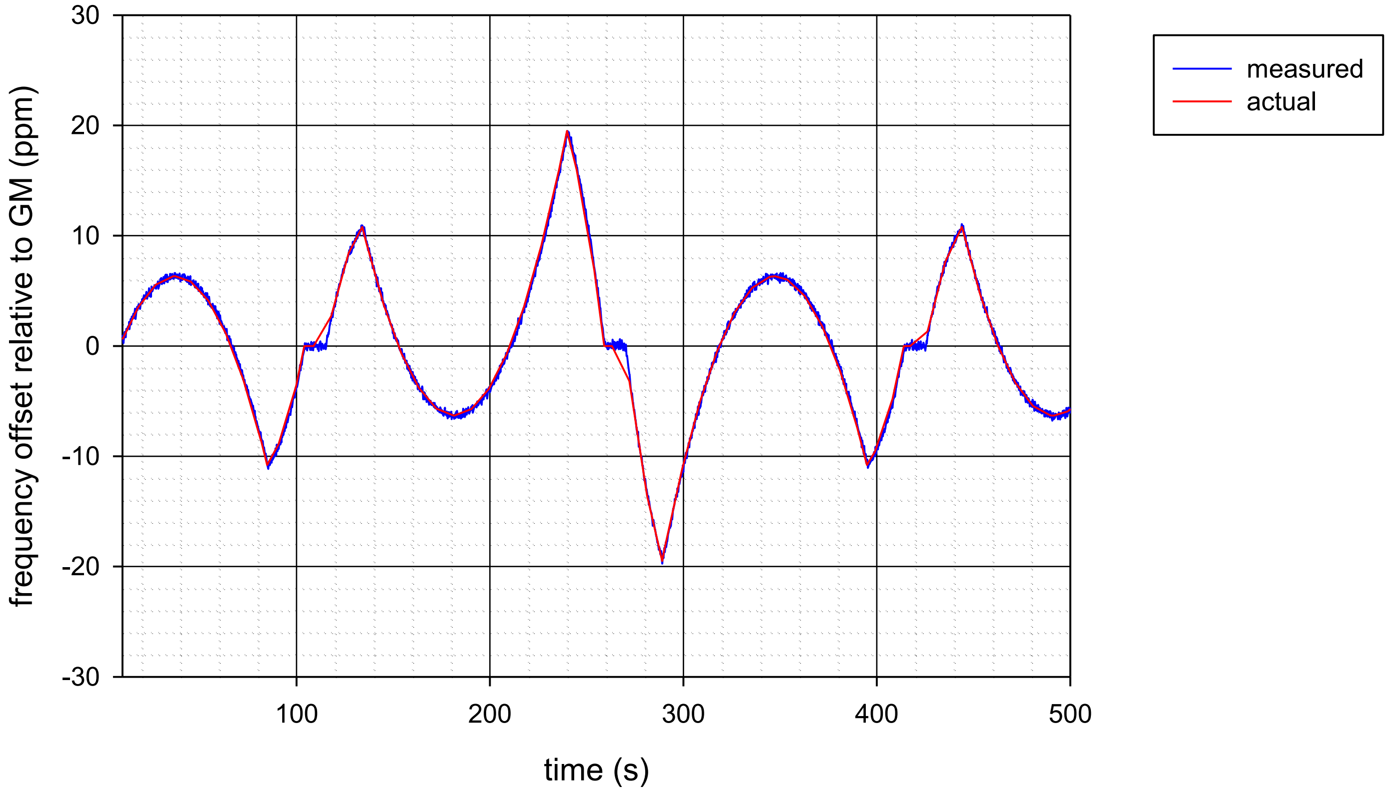
Case16, Subcase 3, Node 68 Detailed Results - 1

Subcase 3, Node 68
Replication 1: 2 - 3150 s
GM time error modeled
Clock Model (all clocks): Frequency vs temperature stability and temperature vs time profile from [3]
Accumulate neighborRateRatio, which is measured with window of size 11 and median
KpKo = 11, KiKo = 65 (f3dB = 2.6 Hz, gain pk = 1.288 dB, zeta = 0.68219)
Initial LocalClock phase waveforms chosen randomly over 100% of cycle
Residence time: 1 ms
Timestamp granularity: 8 ns
30% variation for Sync, 0% for Pdelay Intervals



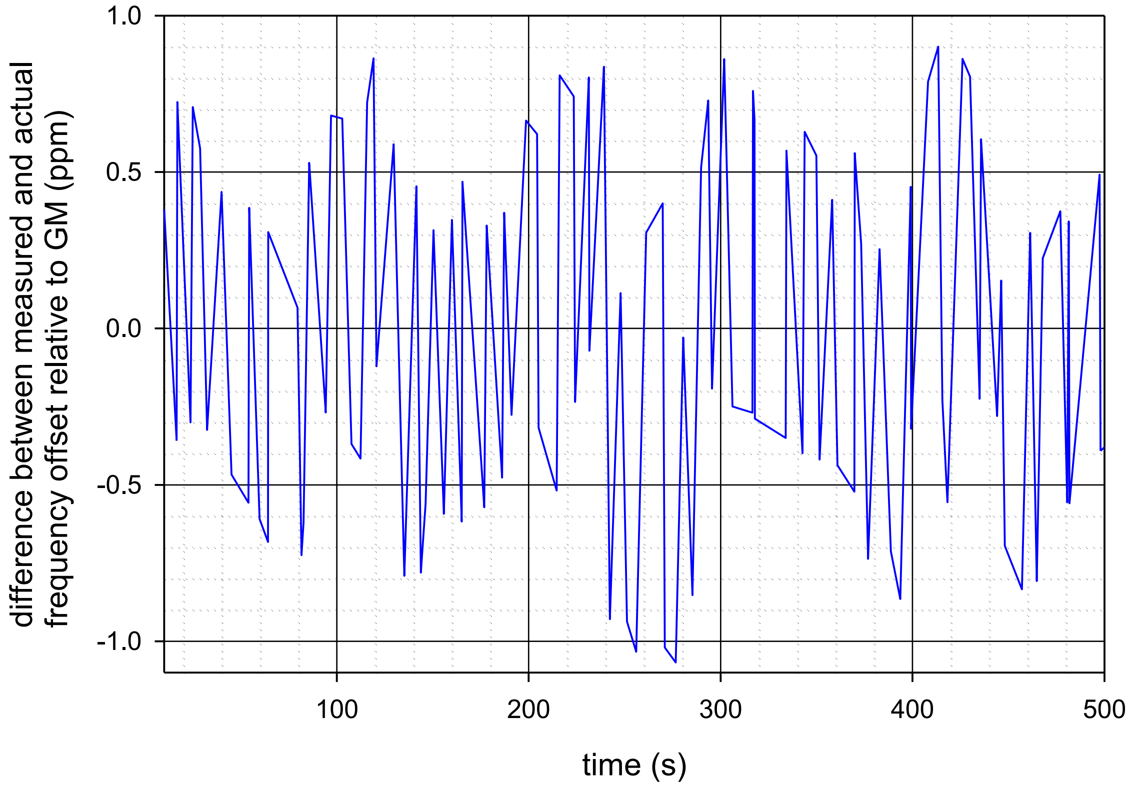
Case16, Subcase 3, Node 68 Detailed Results - 2

Subcase 3, Node 68
Replication 1: 2 - 3150 s
GM time error modeled
Clock Model (all clocks): Frequency vs temperature stability and temperature vs time profile from [3]
Accumulate neighborRateRatio, which is measured with window of size 11 and median
KpKo = 11, KiKo = 65 (f3dB = 2.6 Hz, gain pk = 1.288 dB, zeta = 0.68219)
Initial LocalClock phase waveforms chosen randomly over 100% of cycle
Residence time: 1 ms
Timestamp granularity: 8 ns
30% variation for Sync, 0% for Pdelay Intervals



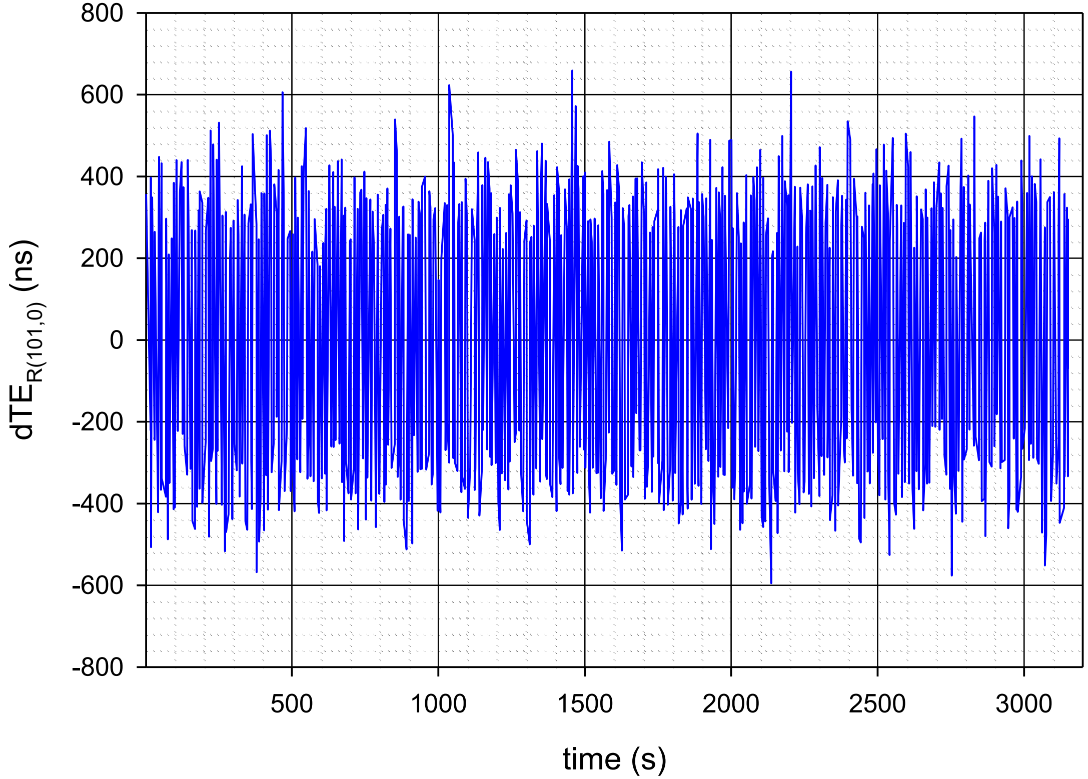
Case16, Subcase 3, Node 68 Detailed Results - 3

Subcase 3, Node 68
Replication 1: 2 - 3150 s
GM time error modeled
Clock Model (all clocks): Frequency vs temperature stability and temperature vs time profile from [3]
Accumulate neighborRateRatio, which is measured with window of size 11 and median
KpKo = 11, KiKo = 65 (f3dB = 2.6 Hz, gain pk = 1.288 dB, zeta = 0.68219)
Initial LocalClock phase waveforms chosen randomly over 100% of cycle
Residence time: 1 ms
Timestamp granularity: 8 ns
30% variation for Sync, 0% for Pdelay Intervals



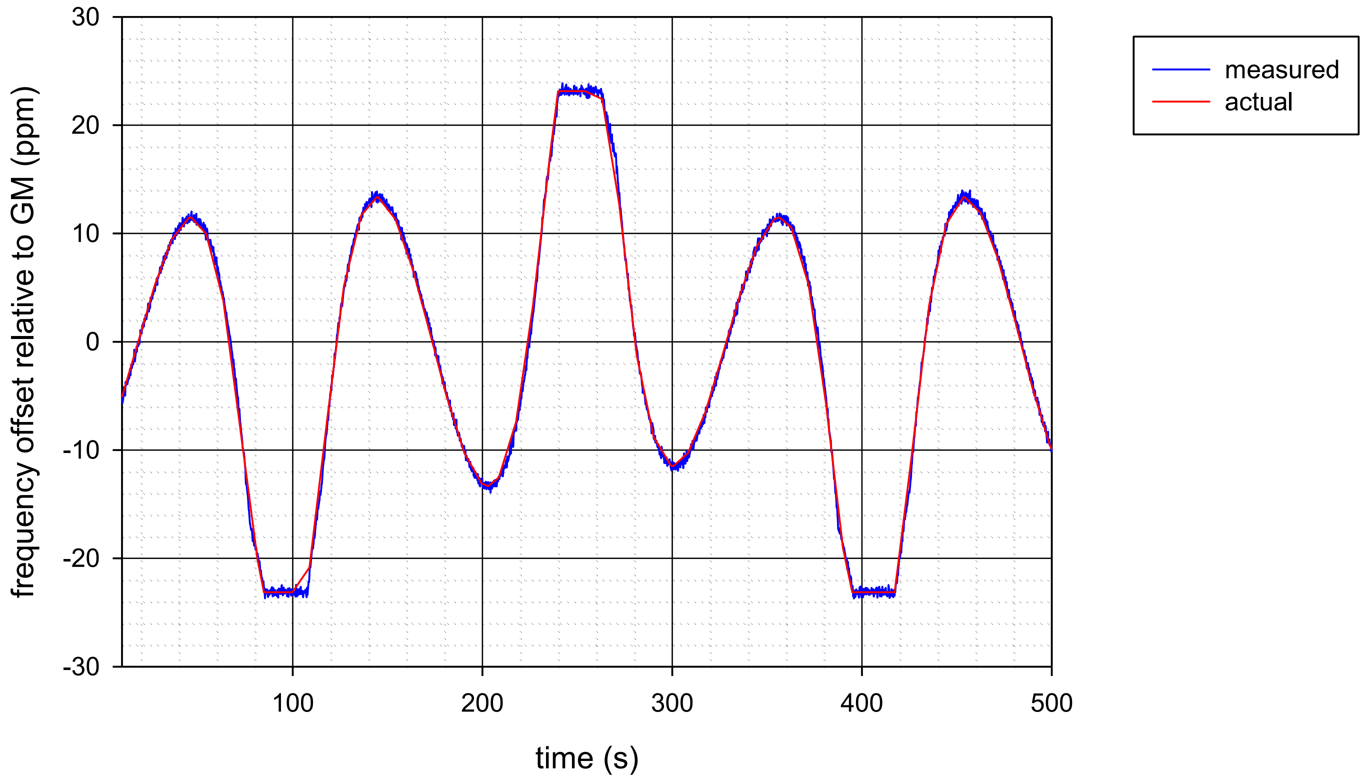
Case16, Subcase 3, Node 101 Detailed Results – 1

Subcase 3, Node 101
Replication 1: 2 - 3150 s
GM time error modeled
Clock Model (all clocks): Frequency vs temperature stability and temperature vs time profile from [3]
Accumulate neighborRateRatio, which is measured with window of size 11 and median
KpKo = 11, KiKo = 65 (f3dB = 2.6 Hz, gain pk = 1.288 dB, zeta = 0.68219)
Initial LocalClock phase waveforms chosen randomly over 100% of cycle
Residence time: 1 ms
Timestamp granularity: 8 ns
30% variation for Sync, 0% for Pdelay Intervals



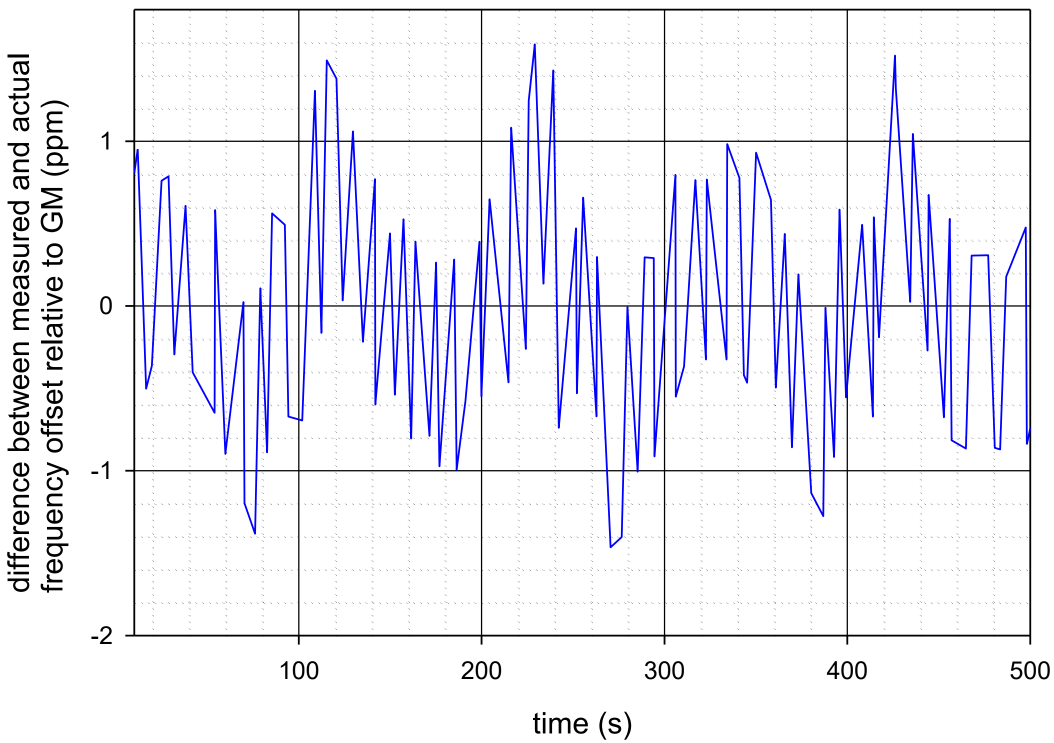
Case16, Subcase 3, Node 101 Detailed Results – 2

Subcase 3, Node 101
Replication 1: 2 - 3150 s
GM time error modeled
Clock Model (all clocks): Frequency vs temperature stability and temperature vs time profile from [3]
Accumulate neighborRateRatio, which is measured with window of size 11 and median
KpKo = 11, KiKo = 65 (f3dB = 2.6 Hz, gain pk = 1.288 dB, zeta = 0.68219)
Initial LocalClock phase waveforms chosen randomly over 100% of cycle
Residence time: 1 ms
Timestamp granularity: 8 ns
30% variation for Sync, 0% for Pdelay Intervals



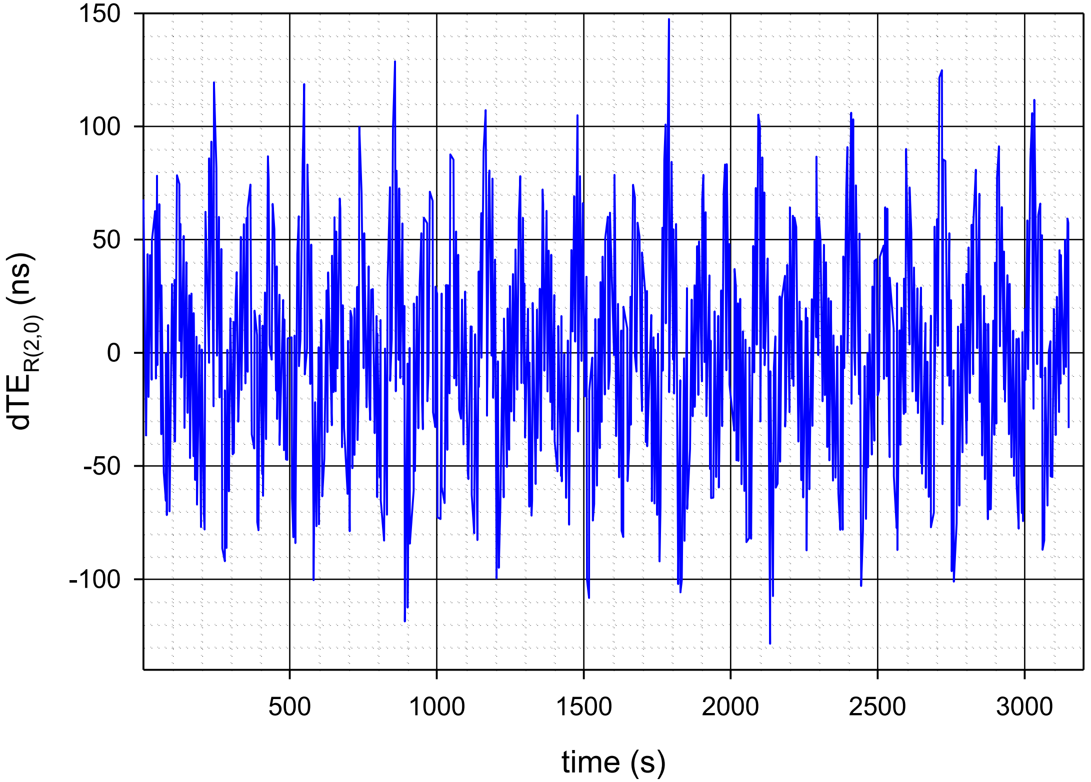
Case16, Subcase 3, Node 101 Detailed Results - 3

Subcase 3, Node 101
Replication 1: 2 - 3150 s
GM time error modeled
Clock Model (all clocks): Frequency vs temperature stability and temperature vs time profile from [3]
Accumulate neighborRateRatio, which is measured with window of size 11 and median
KpKo = 11, KiKo = 65 (f3dB = 2.6 Hz, gain pk = 1.288 dB, zeta = 0.68219)
Initial LocalClock phase waveforms chosen randomly over 100% of cycle
Residence time: 1 ms
Timestamp granularity: 8 ns
30% variation for Sync, 0% for Pdelay Intervals



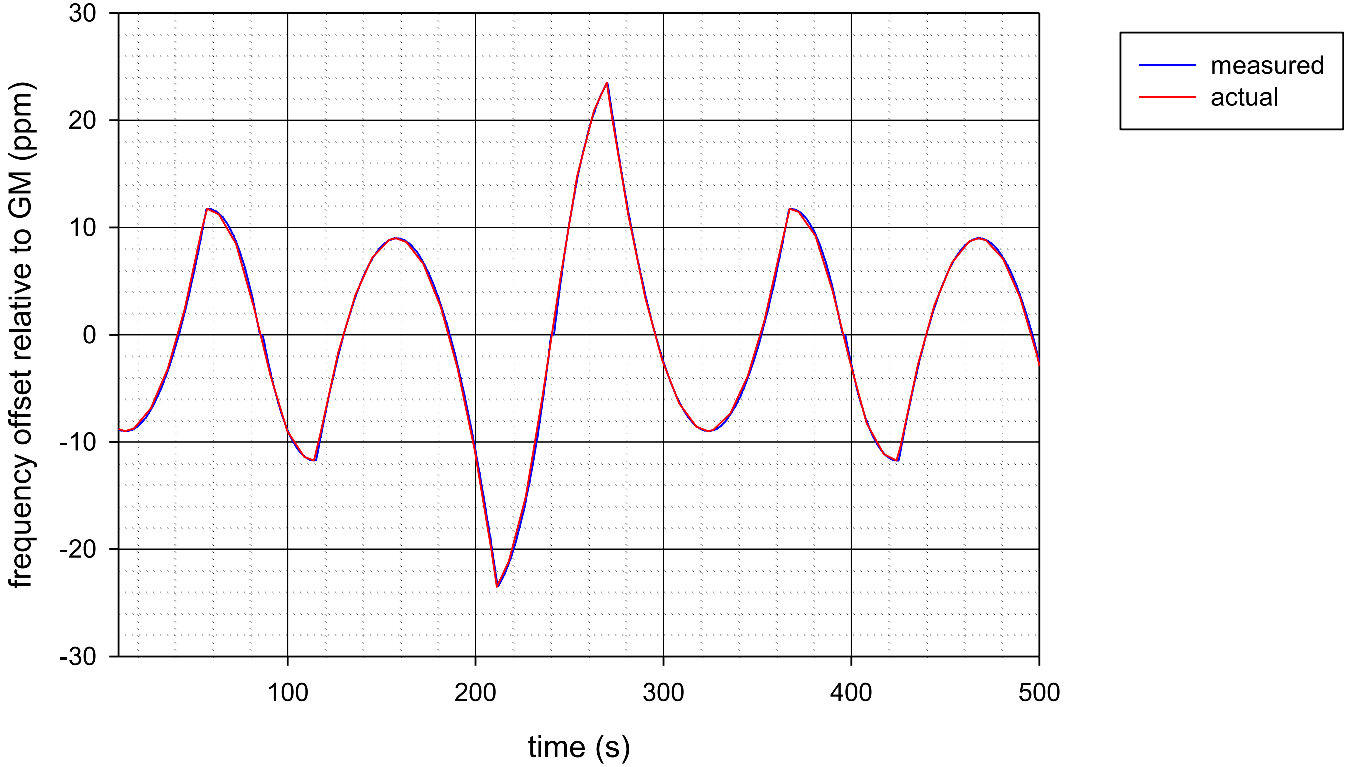
Case16, Subcase 6, Node 2 Detailed Results – 1

Subcase 6, Node 2
Replication 1: 2 - 3150 s
GM time error modeled
Clock Model (all clocks): Frequency vs temperature stability and temperature vs time profile from [3]
Accumulate neighborRateRatio, which is measured with window of size 11 and median
KpKo = 11, KiKo = 65 (f3dB = 2.6 Hz, gain pk = 1.288 dB, zeta = 0.68219)
Initial LocalClock phase waveforms chosen randomly over 100% of cycle
Residence time: 1 ms
Timestamp granularity: 8 ns
30% variation for Sync, 30% for Pdelay Intervals



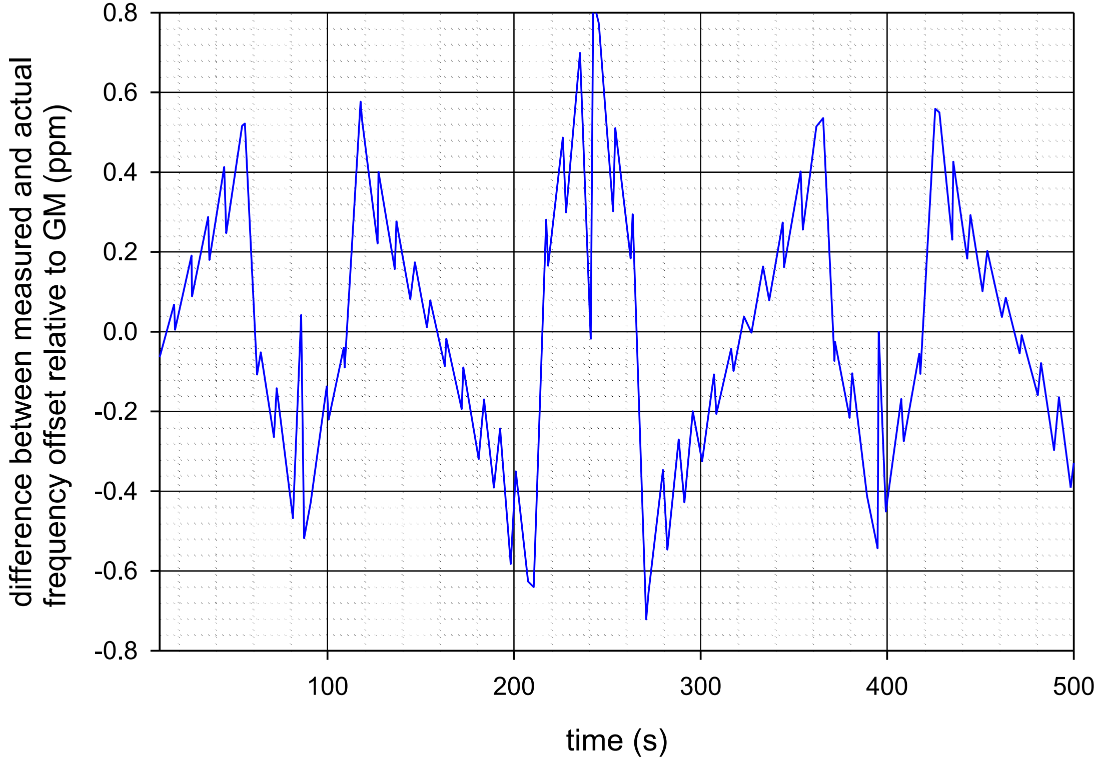
Case16, Subcase 6, Node 2 Detailed Results – 2

Subcase 6, Node 2
Replication 1: 2 - 3150 s
GM time error modeled
Clock Model (all clocks): Frequency vs temperature stability and temperature vs time profile from [3]
Accumulate neighborRateRatio, which is measured with window of size 11 and median
KpKo = 11, KiKo = 65 (f3dB = 2.6 Hz, gain pk = 1.288 dB, zeta = 0.68219)
Initial LocalClock phase waveforms chosen randomly over 100% of cycle
Residence time: 1 ms
Timestamp granularity: 8 ns
30% variation for Sync, 30% for Pdelay Intervals



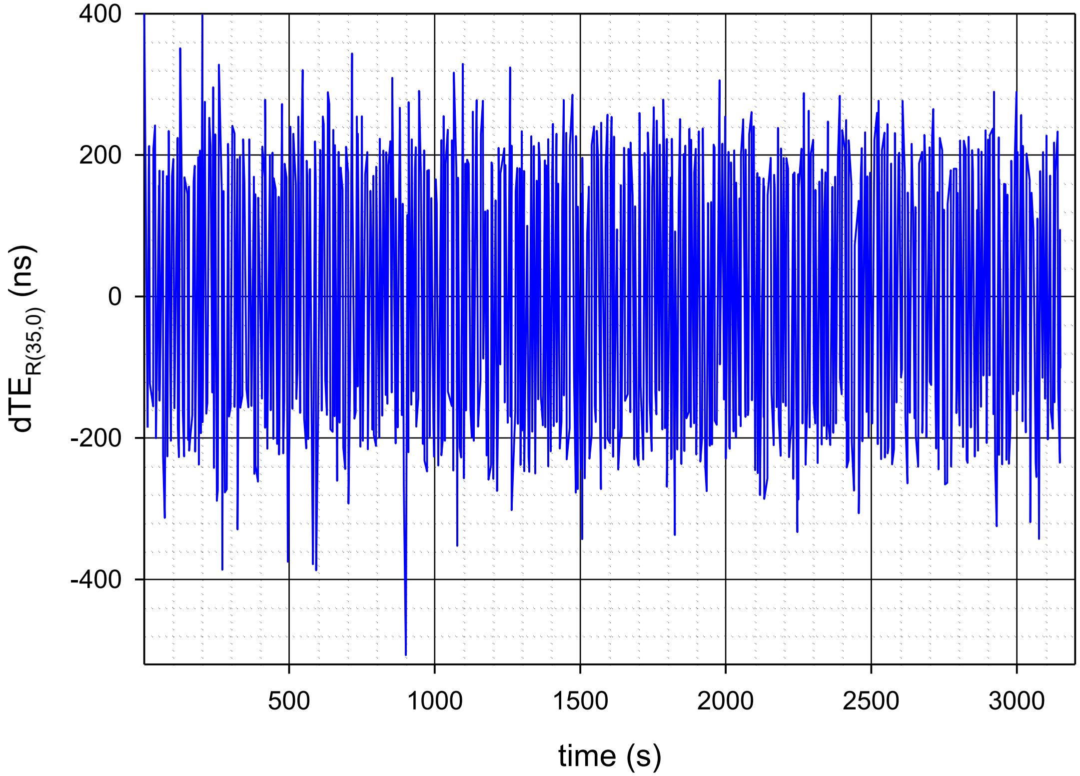
Case16, Subcase 6, Node 2 Detailed Results – 3

Subcase 6, Node 2
Replication 1: 2 - 3150 s
GM time error modeled
Clock Model (all clocks): Frequency vs temperature stability and temperature vs time profile from [3]
Accumulate neighborRateRatio, which is measured with window of size 11 and median
KpKo = 11, KiKo = 65 (f3dB = 2.6 Hz, gain pk = 1.288 dB, zeta = 0.68219)
Initial LocalClock phase waveforms chosen randomly over 100% of cycle
Residence time: 1 ms
Timestamp granularity: 8 ns
30% variation for Sync, 30% for Pdelay Intervals



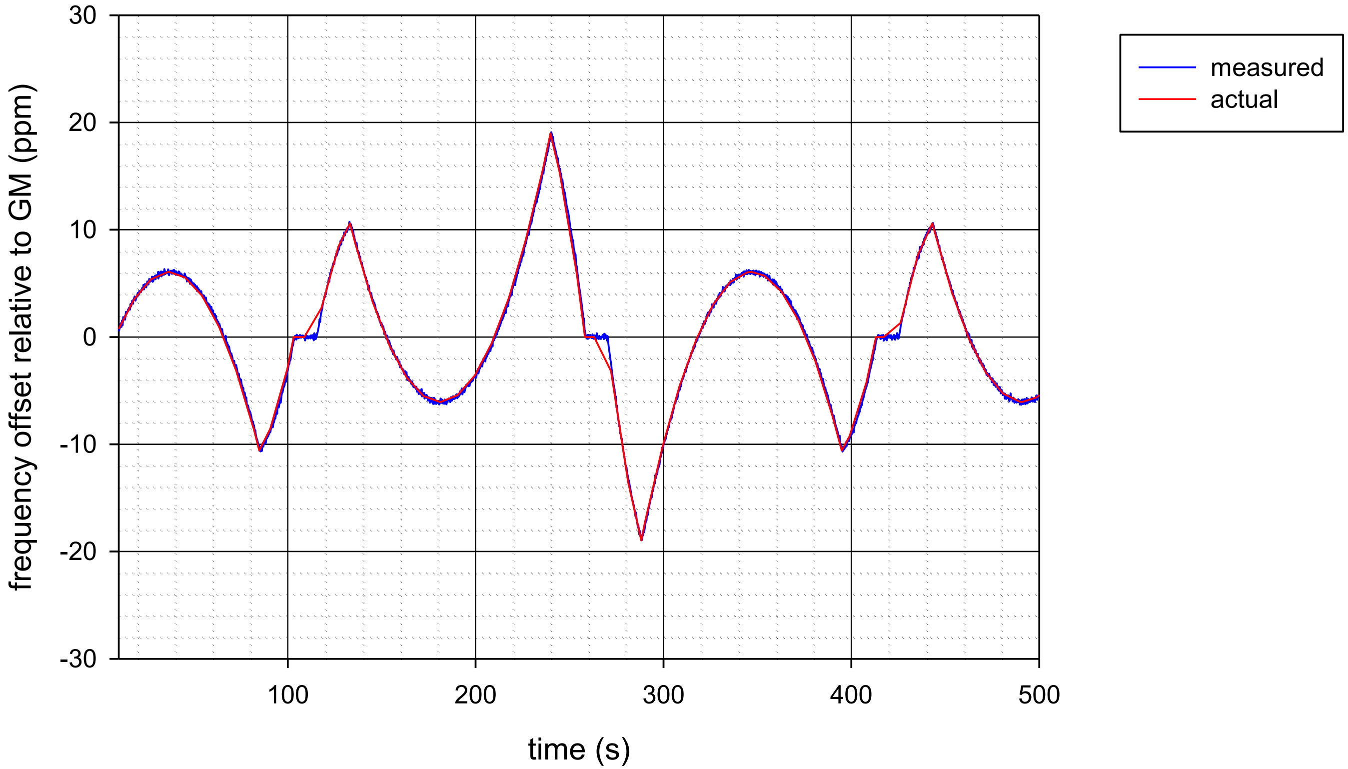
Case16, Subcase 6, Node 35 Detailed Results - 1

Subcase 6, Node 35
Replication 1: 2 - 3150 s
GM time error modeled
Clock Model (all clocks): Frequency vs temperature stability and temperature vs time profile from [3]
Accumulate neighborRateRatio, which is measured with window of size 11 and median
KpKo = 11, KiKo = 65 (f3dB = 2.6 Hz, gain pk = 1.288 dB, zeta = 0.68219)
Initial LocalClock phase waveforms chosen randomly over 100% of cycle
Residence time: 1 ms
Timestamp granularity: 8 ns
30% variation for Sync, 30% for Pdelay Intervals



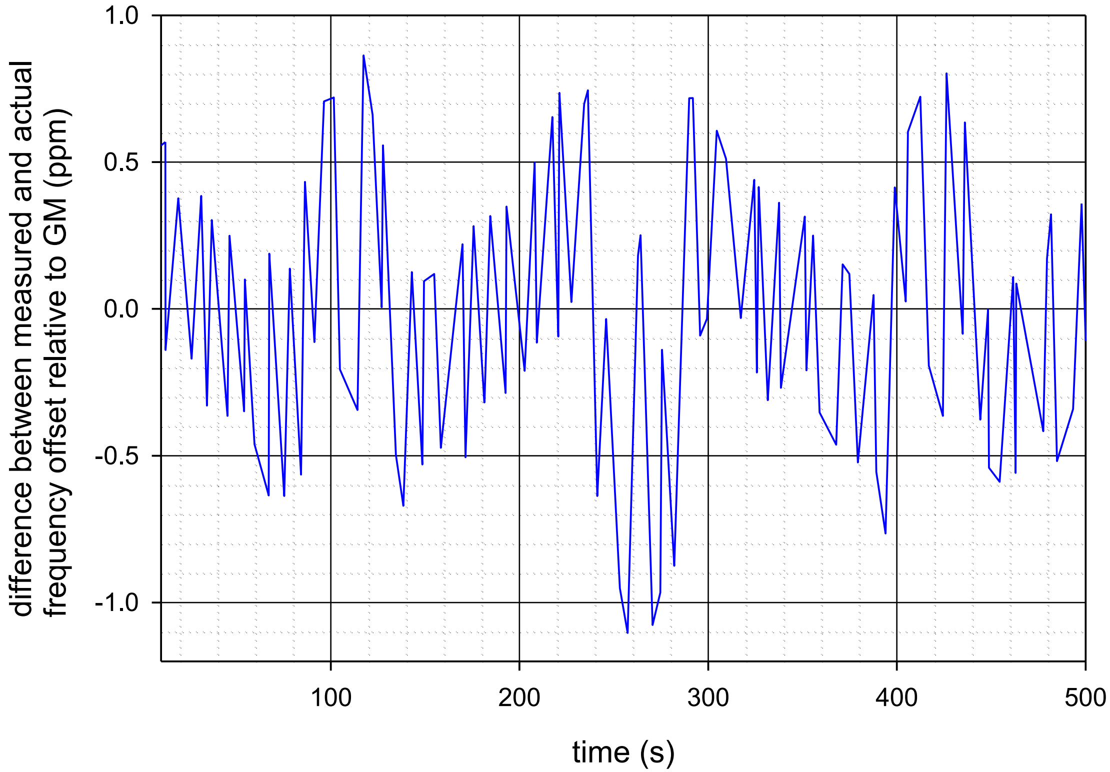
Case16, Subcase 6, Node 35 Detailed Results - 2

Subcase 6, Node 35
Replication 1: 2 - 3150 s
GM time error modeled
Clock Model (all clocks): Frequency vs temperature stability and temperature vs time profile from [3]
Accumulate neighborRateRatio, which is measured with window of size 11 and median
KpKo = 11, KiKo = 65 (f3dB = 2.6 Hz, gain pk = 1.288 dB, zeta = 0.68219)
Initial LocalClock phase waveforms chosen randomly over 100% of cycle
Residence time: 1 ms
Timestamp granularity: 8 ns
30% variation for Sync, 30% for Pdelay Intervals



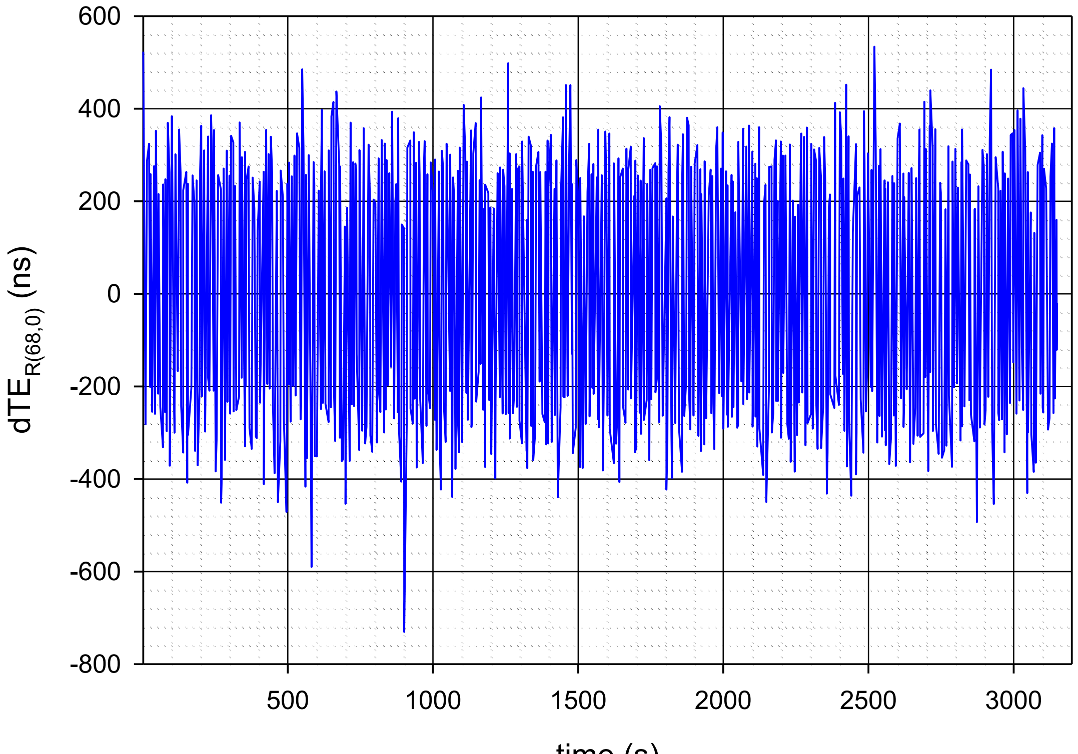
Case16, Subcase 6, Node 35 Detailed Results - 3

Subcase 6, Node 35
Replication 1: 2 - 3150 s
GM time error modeled
Clock Model (all clocks): Frequency vs temperature stability and temperature vs time profile from [3]
Accumulate neighborRateRatio, which is measured with window of size 11 and median
KpKo = 11, KiKo = 65 (f3dB = 2.6 Hz, gain pk = 1.288 dB, zeta = 0.68219)
Initial LocalClock phase waveforms chosen randomly over 100% of cycle
Residence time: 1 ms
Timestamp granularity: 8 ns
30% variation for Sync, 30% for Pdelay Intervals



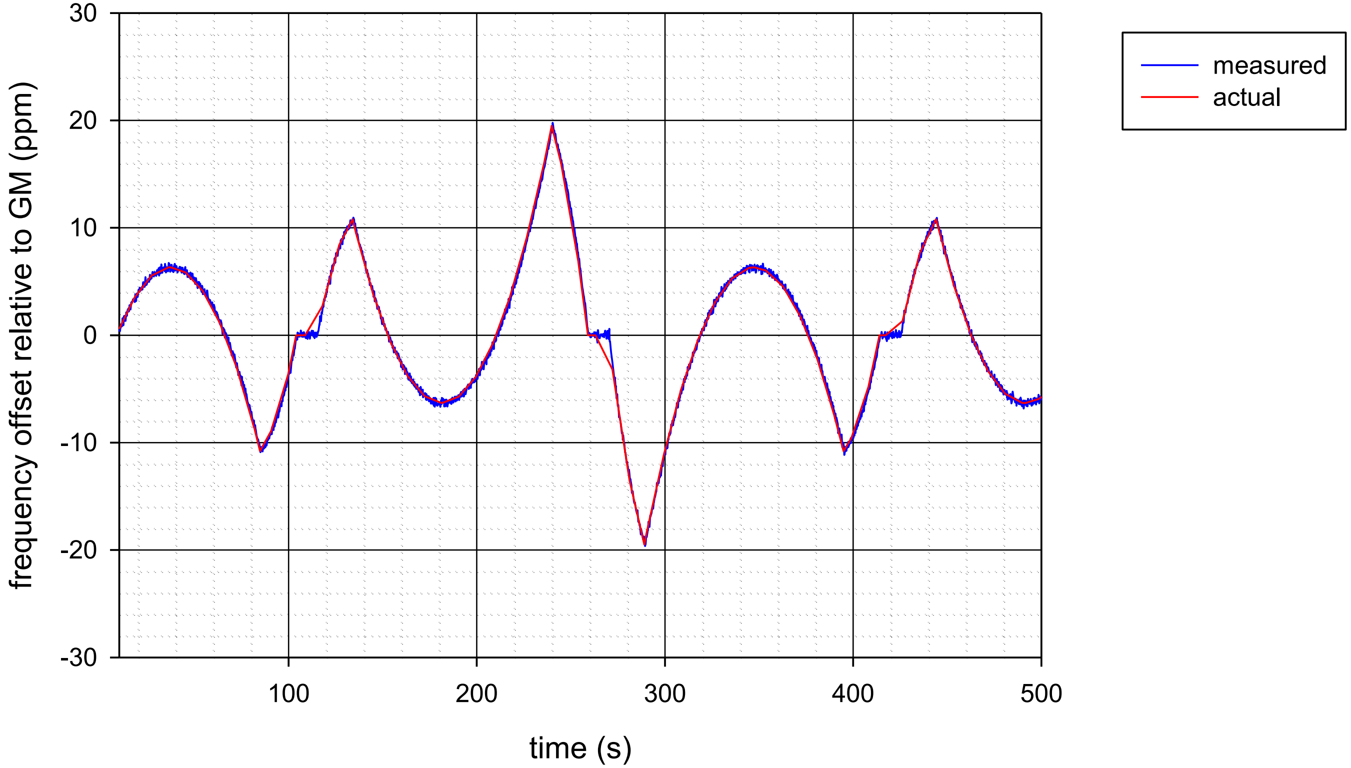
Case16, Subcase 6, Node 68 Detailed Results - 1

Subcase 6, Node 68
Replication 1: 2 - 3150 s
GM time error modeled
Clock Model (all clocks): Frequency vs temperature stability and temperature vs time profile from [3]
Accumulate neighborRateRatio, which is measured with window of size 11 and median
KpKo = 11, KiKo = 65 (f3dB = 2.6 Hz, gain pk = 1.288 dB, zeta = 0.68219)
Initial LocalClock phase waveforms chosen randomly over 100% of cycle
Residence time: 1 ms
Timestamp granularity: 8 ns
30% variation for Sync, 30% for Pdelay Intervals



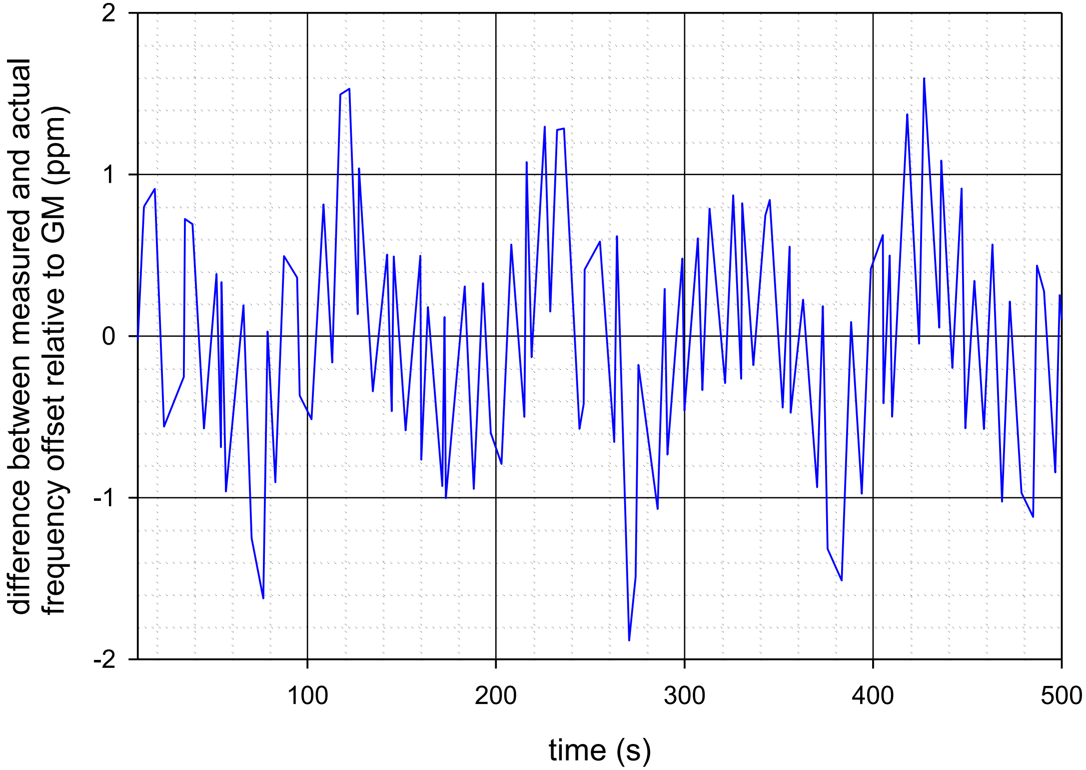
Case16, Subcase 6, Node 68 Detailed Results - 2

Subcase 6, Node 68
Replication 1: 2 - 3150 s
GM time error modeled
Clock Model (all clocks): Frequency vs temperature stability and temperature vs time profile from [3]
Accumulate neighborRateRatio, which is measured with window of size 11 and median
KpKo = 11, KiKo = 65 (f3dB = 2.6 Hz, gain pk = 1.288 dB, zeta = 0.68219)
Initial LocalClock phase waveforms chosen randomly over 100% of cycle
Residence time: 1 ms
Timestamp granularity: 8 ns
30% variation for Sync, 30% for Pdelay Intervals



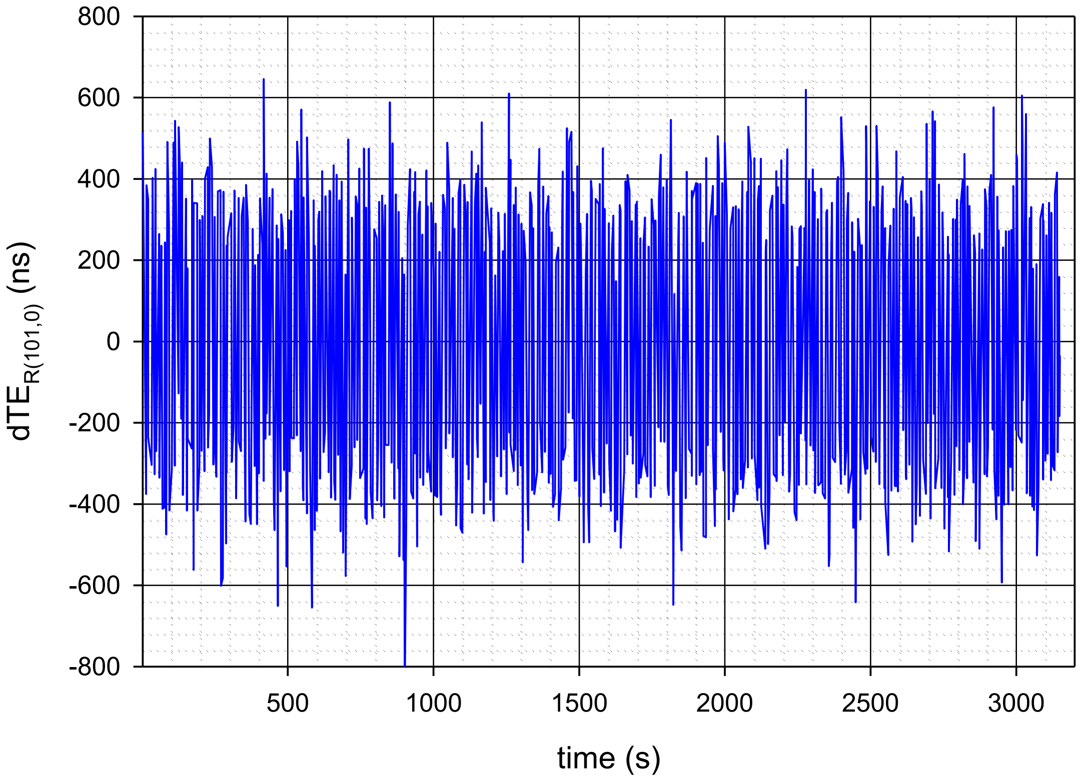
Case16, Subcase 6, Node 68 Detailed Results - 3

Subcase 6, Node 68
Replication 1: 2 - 3150 s
GM time error modeled
Clock Model (all clocks): Frequency vs temperature stability and temperature vs time profile from [3]
Accumulate neighborRateRatio, which is measured with window of size 11 and median
KpKo = 11, KiKo = 65 (f3dB = 2.6 Hz, gain pk = 1.288 dB, zeta = 0.68219)
Initial LocalClock phase waveforms chosen randomly over 100% of cycle
Residence time: 1 ms
Timestamp granularity: 8 ns
30% variation for Sync, 30% for Pdelay Intervals



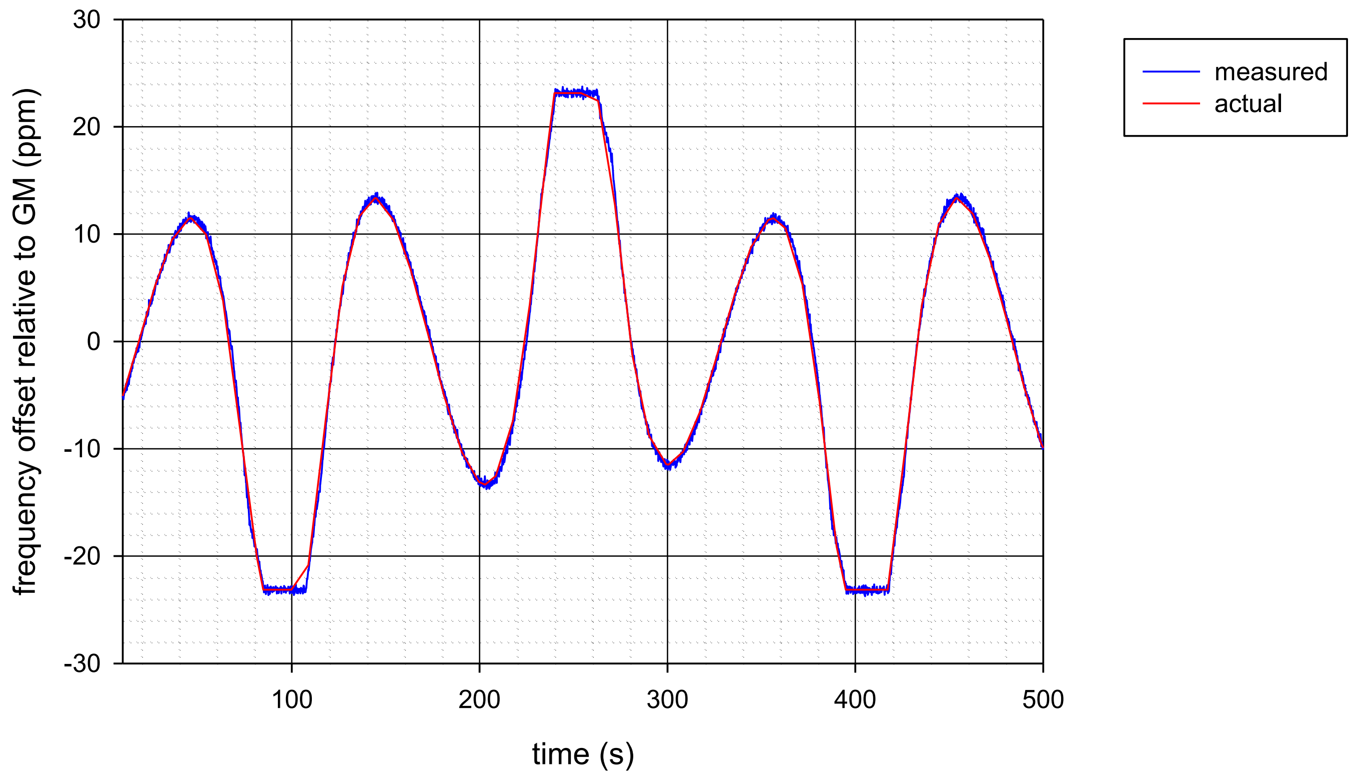
Case16, Subcase 6, Node 101 Detailed Results – 1

Subcase 6, Node 101
Replication 1: 2 - 3150 s
GM time error modeled
Clock Model (all clocks): Frequency vs temperature stability and temperature vs time profile from [3]
Accumulate neighborRateRatio, which is measured with window of size 11 and median
KpKo = 11, KiKo = 65 (f3dB = 2.6 Hz, gain pk = 1.288 dB, zeta = 0.68219)
Initial LocalClock phase waveforms chosen randomly over 100% of cycle
Residence time: 1 ms
Timestamp granularity: 8 ns
30% variation for Sync, 30% for Pdelay Intervals



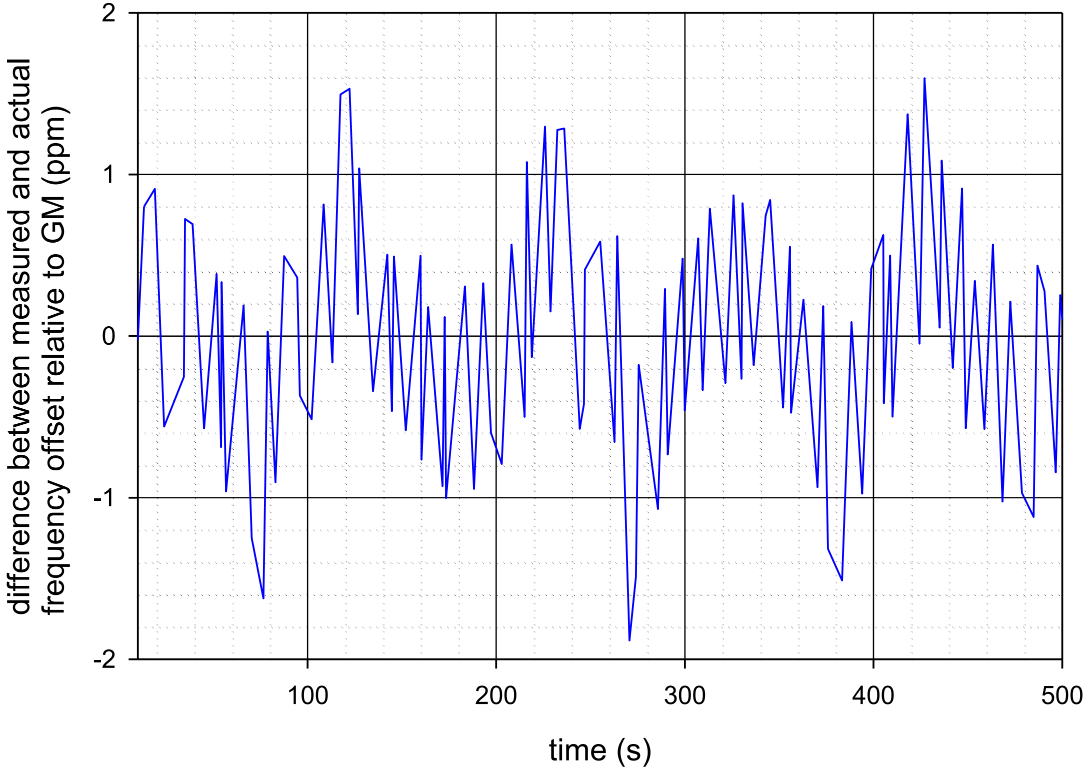
Case16, Subcase 6, Node 101 Detailed Results – 2

Subcase 6, Node 101
Replication 1: 2 - 3150 s
GM time error modeled
Clock Model (all clocks): Frequency vs temperature stability and temperature vs time profile from [3]
Accumulate neighborRateRatio, which is measured with window of size 11 and median
KpKo = 11, KiKo = 65 (f3dB = 2.6 Hz, gain pk = 1.288 dB, zeta = 0.68219)
Initial LocalClock phase waveforms chosen randomly over 100% of cycle
Residence time: 1 ms
Timestamp granularity: 8 ns
30% variation for Sync, 30% for Pdelay Intervals



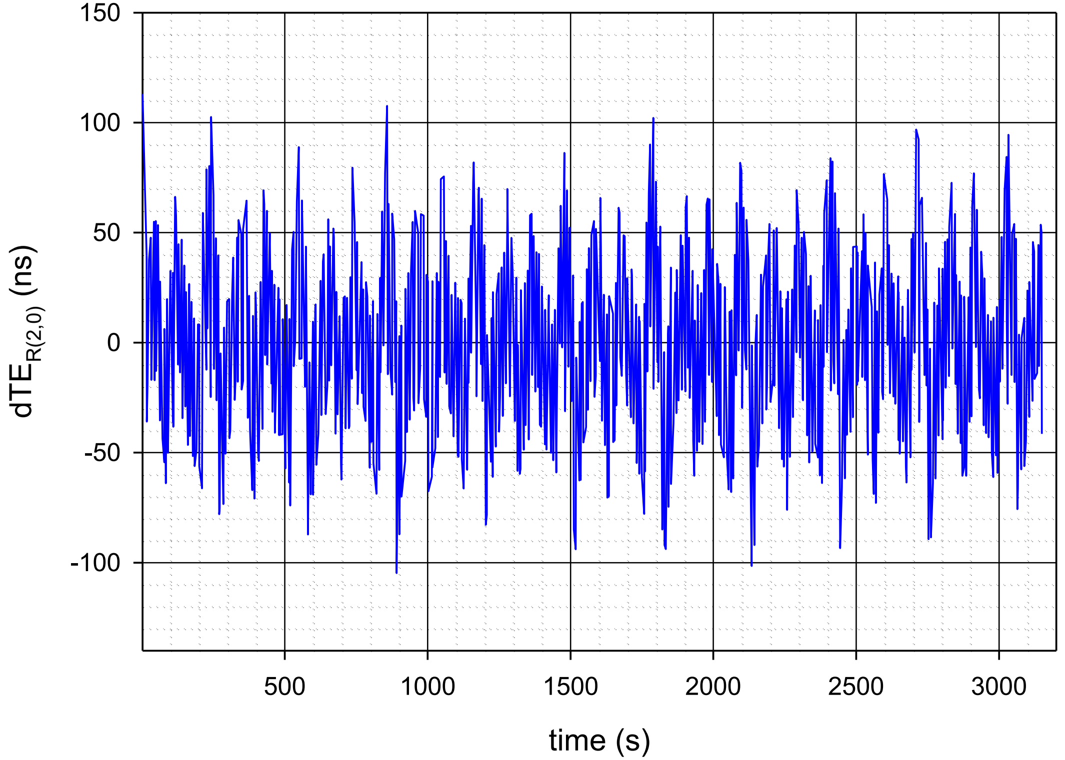
Case16, Subcase 6, Node 101 Detailed Results – 3

Subcase 6, Node 101
Replication 1: 2 - 3150 s
GM time error modeled
Clock Model (all clocks): Frequency vs temperature stability and temperature vs time profile from [3]
Accumulate neighborRateRatio, which is measured with window of size 11 and median
KpKo = 11, KiKo = 65 (f3dB = 2.6 Hz, gain pk = 1.288 dB, zeta = 0.68219)
Initial LocalClock phase waveforms chosen randomly over 100% of cycle
Residence time: 1 ms
Timestamp granularity: 8 ns
30% variation for Sync, 30% for Pdelay Intervals



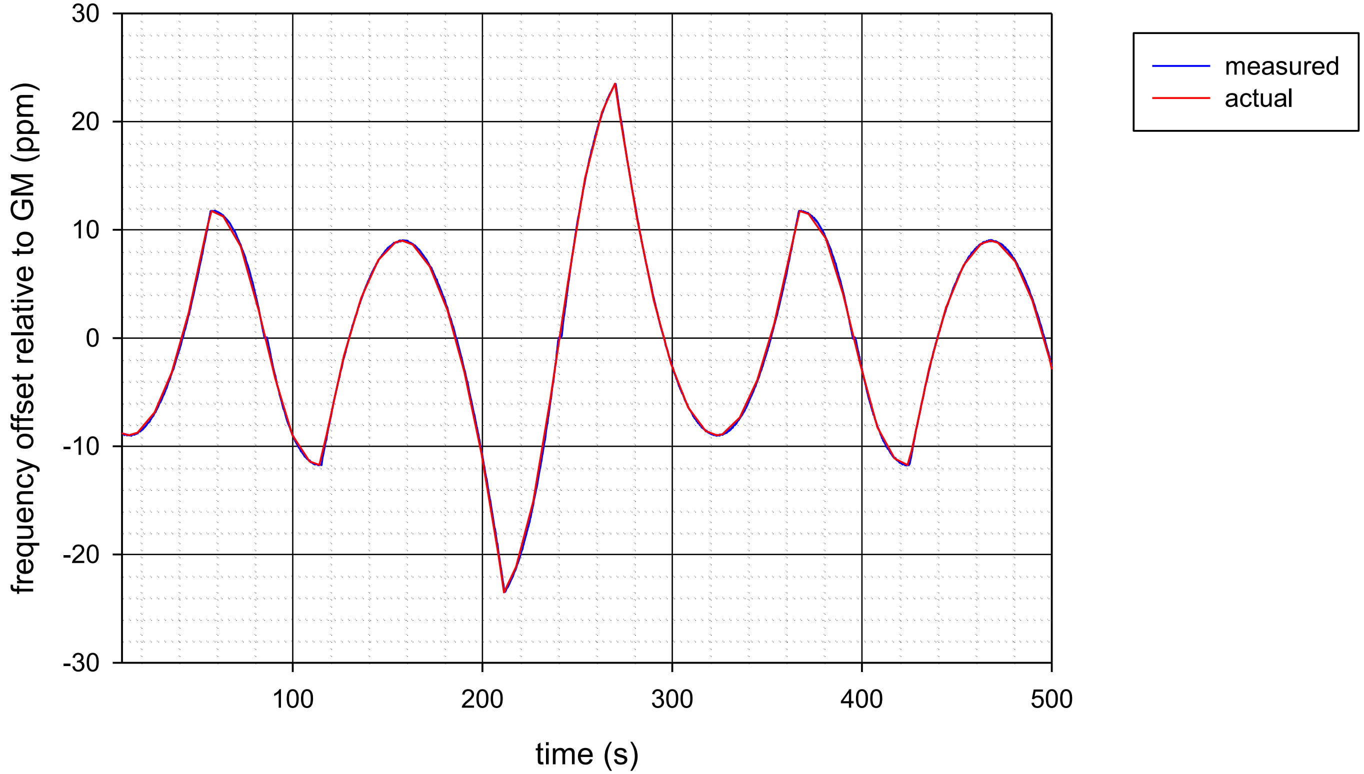
Case16, Subcase 12, Node 2 Detailed Results - 1

Subcase 12, Node 2
Replication 1: 2 - 3150 s
GM time error modeled
Clock Model (all clocks): Frequency vs temperature stability and temperature vs time profile from [3]
Accumulate neighborRateRatio, which is measured with window of size 7 and median
KpKo = 11, KiKo = 65 (f3dB = 2.6 Hz, gain pk = 1.288 dB, zeta = 0.68219)
Initial LocalClock phase waveforms chosen randomly over 100% of cycle
Residence time: 1 ms
Timestamp granularity: 8 ns
30% variation for Sync, 30% for Pdelay Intervals



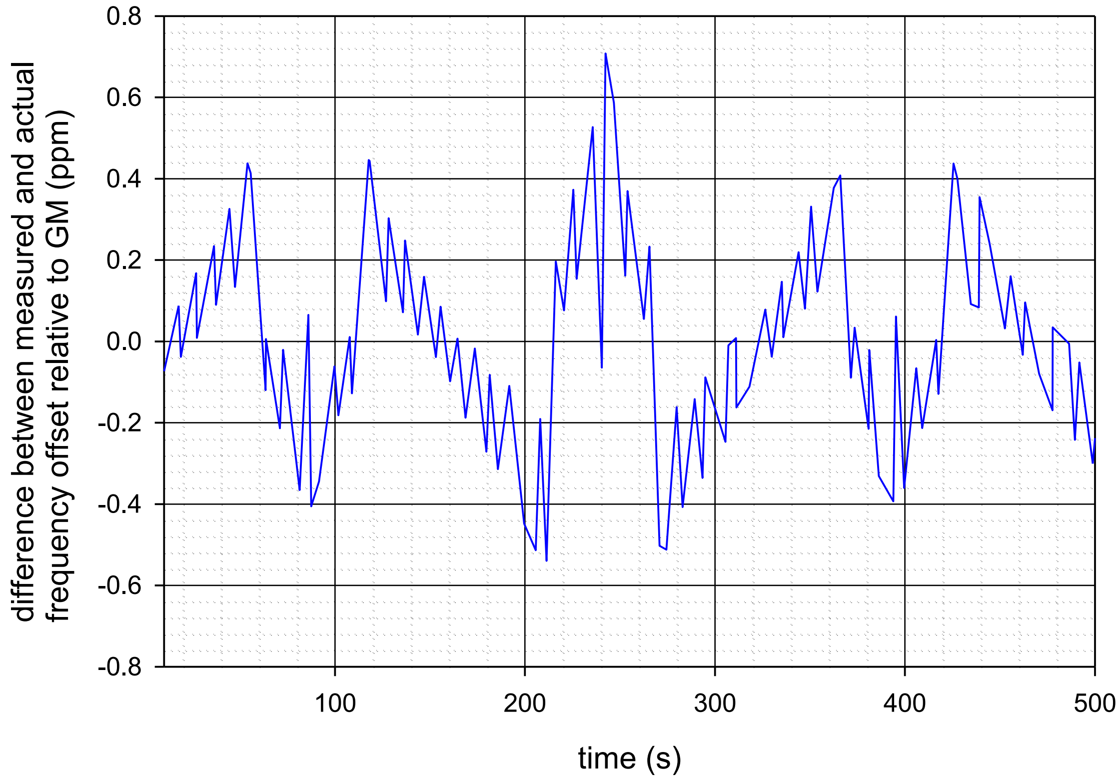
Case16, Subcase 12, Node 2 Detailed Results - 2

Subcase 12, Node 2
Replication 1: 2 - 3150 s
GM time error modeled
Clock Model (all clocks): Frequency vs temperature stability and temperature vs time profile from [3]
Accumulate neighborRateRatio, which is measured with window of size 7 and median
KpKo = 11, KiKo = 65 (f3dB = 2.6 Hz, gain pk = 1.288 dB, zeta = 0.68219)
Initial LocalClock phase waveforms chosen randomly over 100% of cycle
Residence time: 1 ms
Timestamp granularity: 8 ns
30% variation for Sync, 30% for Pdelay Intervals



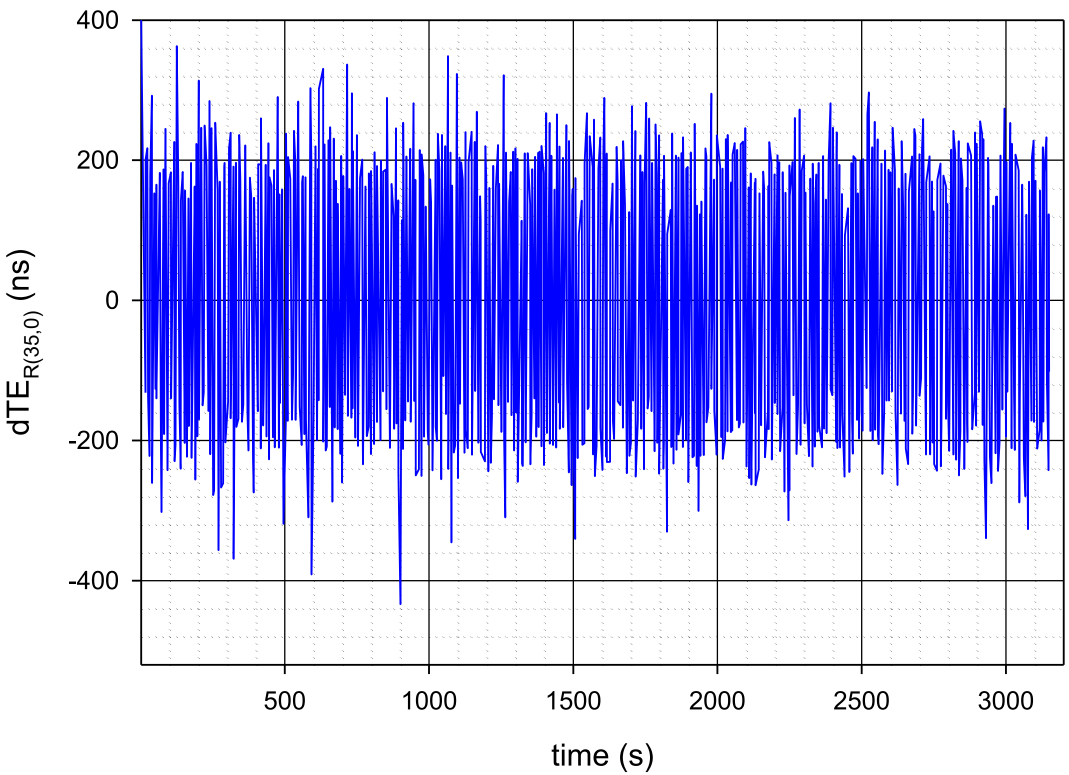
Case16, Subcase 12, Node 2 Detailed Results - 3

Subcase 12, Node 2
Replication 1: 2 - 3150 s
GM time error modeled
Clock Model (all clocks): Frequency vs temperature stability and temperature vs time profile from [3]
Accumulate neighborRateRatio, which is measured with window of size 7 and median
KpKo = 11, KiKo = 65 (f3dB = 2.6 Hz, gain pk = 1.288 dB, zeta = 0.68219)
Initial LocalClock phase waveforms chosen randomly over 100% of cycle
Residence time: 1 ms
Timestamp granularity: 8 ns
30% variation for Sync, 30% for Pdelay Intervals



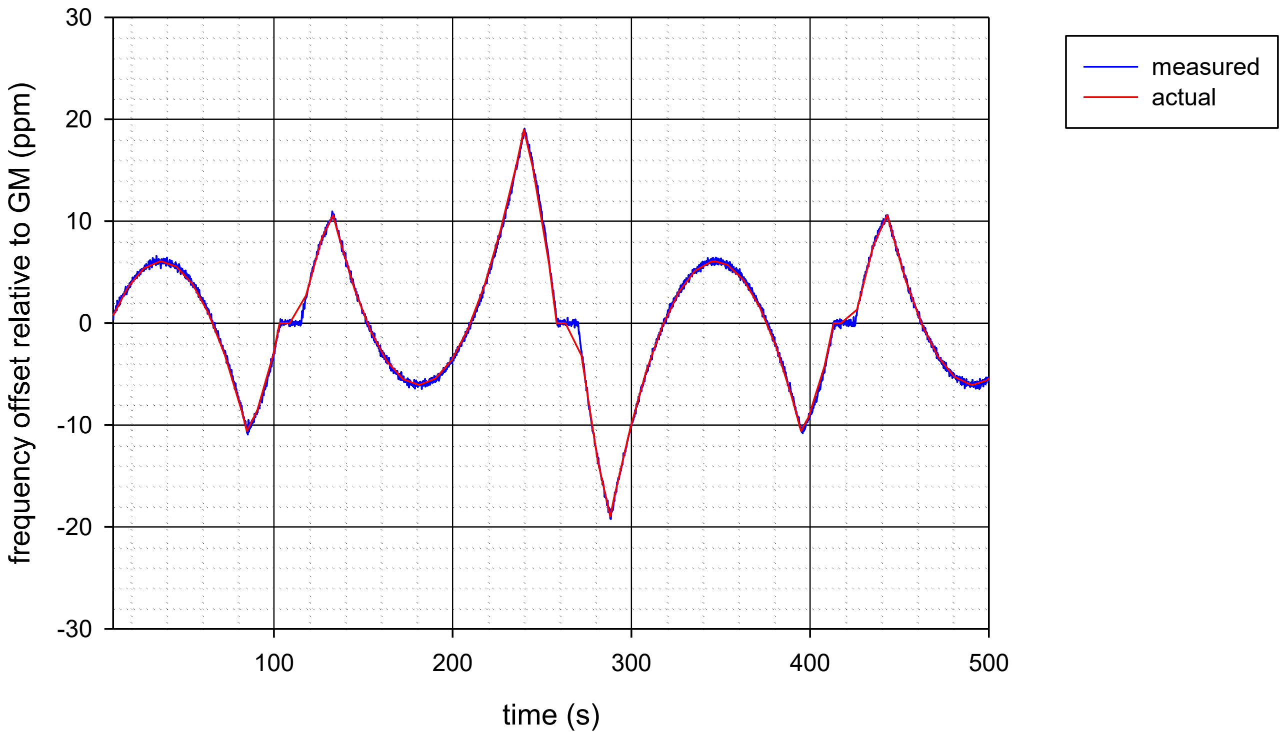
Case16, Subcase 12, Node 35 Detailed Results – 1

Subcase 12, Node 35
Replication 1: 2 - 3150 s
GM time error modeled
Clock Model (all clocks): Frequency vs temperature stability and temperature vs time profile from [3]
Accumulate neighborRateRatio, which is measured with window of size 7 and median
KpKo = 11, KiKo = 65 (f3dB = 2.6 Hz, gain pk = 1.288 dB, zeta = 0.68219)
Initial LocalClock phase waveforms chosen randomly over 100% of cycle
Residence time: 1 ms
Timestamp granularity: 8 ns
30% variation for Sync, 30% for Pdelay Intervals



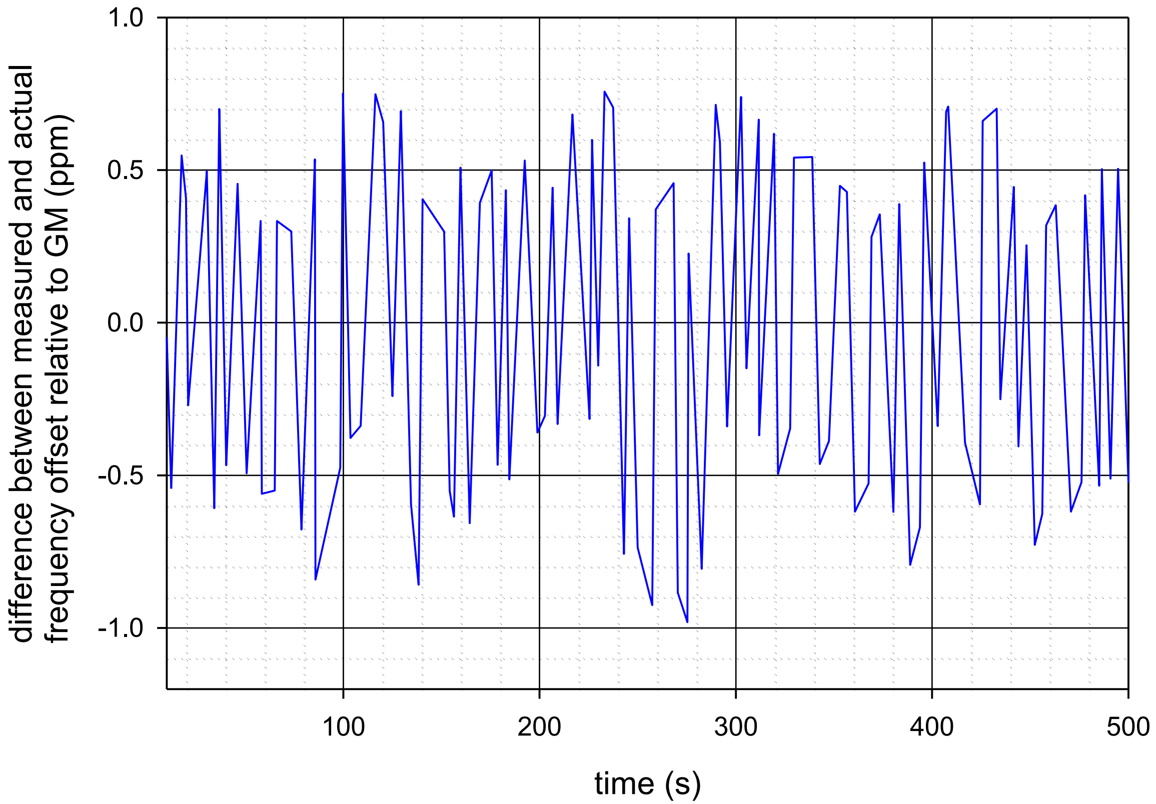
Case16, Subcase 12, Node 35 Detailed Results – 2

Subcase 12, Node 35
Replication 1: 2 - 3150 s
GM time error modeled
Clock Model (all clocks): Frequency vs temperature stability and temperature vs time profile from [3]
Accumulate neighborRateRatio, which is measured with window of size 7 and median
KpKo = 11, KiKo = 65 (f3dB = 2.6 Hz, gain pk = 1.288 dB, zeta = 0.68219)
Initial LocalClock phase waveforms chosen randomly over 100% of cycle
Residence time: 1 ms
Timestamp granularity: 8 ns
30% variation for Sync, 30% for Pdelay Intervals



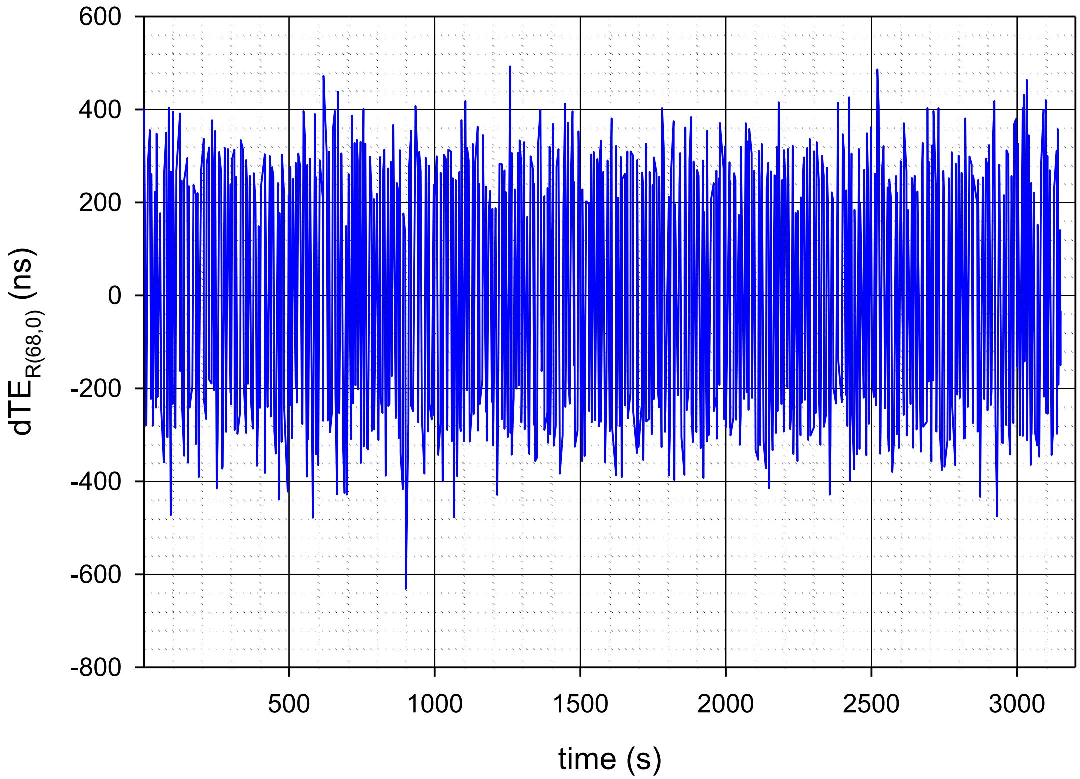
Case16, Subcase 12, Node 35 Detailed Results – 3

- Subcase 12, Node 35
  Replication 1: 2 - 3150 s
  GM time error modeled
  Clock Model (all clocks): Frequency vs temperature stability and temperature vs time profile from [3]
  Accumulate neighborRateRatio, which is measured with window of size 7 and median
  KpKo = 11, KiKo = 65 (f3dB = 2.6 Hz, gain pk = 1.288 dB, zeta = 0.68219)
  Initial LocalClock phase waveforms chosen randomly over 100% of cycle
  Residence time: 1 ms
  Timestamp granularity: 8 ns
  30% variation for Sync, 30% for Pdelay Intervals



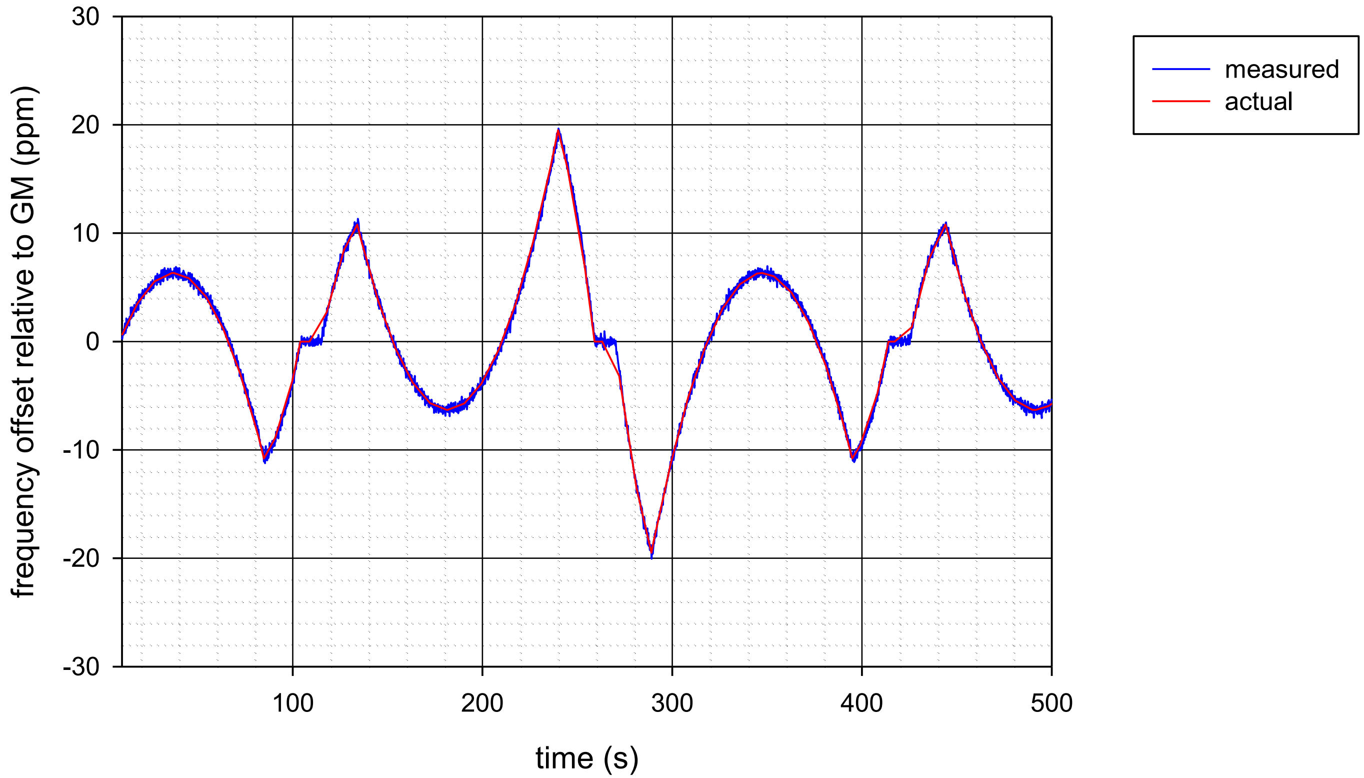
Case16, Subcase 12, Node 68 Detailed Results – 1

Subcase 12, Node 68
Replication 1: 2 - 3150 s
GM time error modeled
Clock Model (all clocks): Frequency vs temperature stability and temperature vs time profile from [3]
Accumulate neighborRateRatio, which is measured with window of size 7 and median
KpKo = 11, KiKo = 65 (f3dB = 2.6 Hz, gain pk = 1.288 dB, zeta = 0.68219)
Initial LocalClock phase waveforms chosen randomly over 100% of cycle
Residence time: 1 ms
Timestamp granularity: 8 ns
30% variation for Sync, 30% for Pdelay Intervals



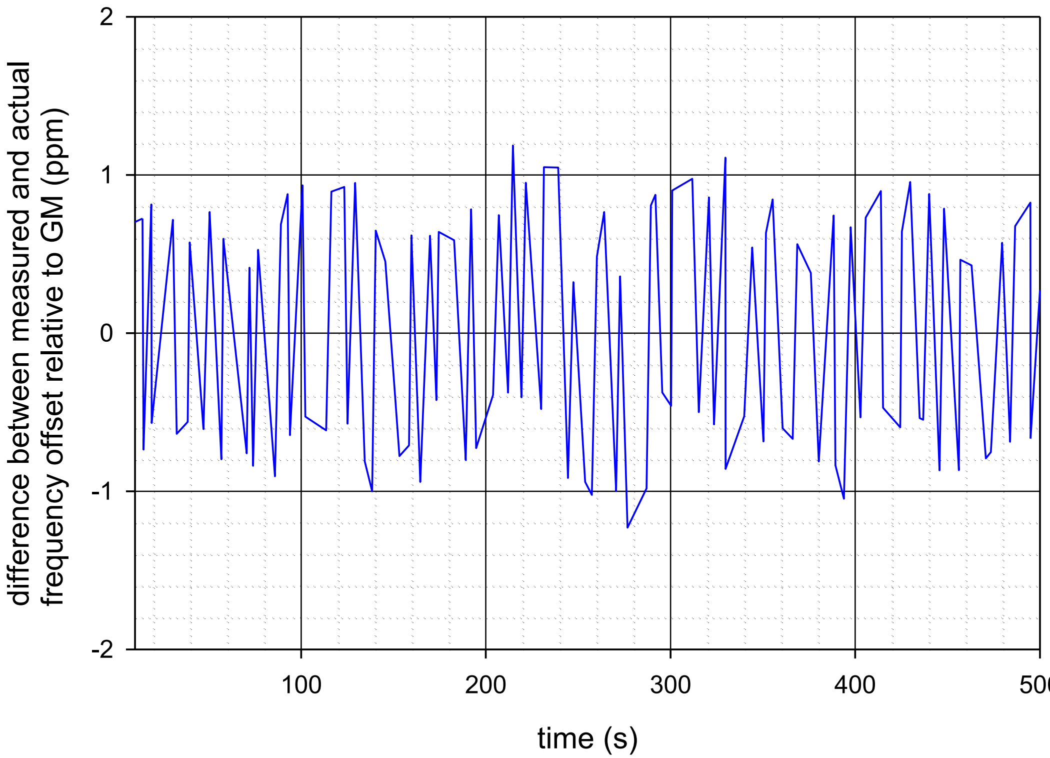
Case16, Subcase 12, Node 68 Detailed Results – 2

Subcase 12, Node 68
Replication 1: 2 - 3150 s
GM time error modeled
Clock Model (all clocks): Frequency vs temperature stability and temperature vs time profile from [3]
Accumulate neighborRateRatio, which is measured with window of size 7 and median
KpKo = 11, KiKo = 65 (f3dB = 2.6 Hz, gain pk = 1.288 dB, zeta = 0.68219)
Initial LocalClock phase waveforms chosen randomly over 100% of cycle
Residence time: 1 ms
Timestamp granularity: 8 ns
30% variation for Sync, 30% for Pdelay Intervals



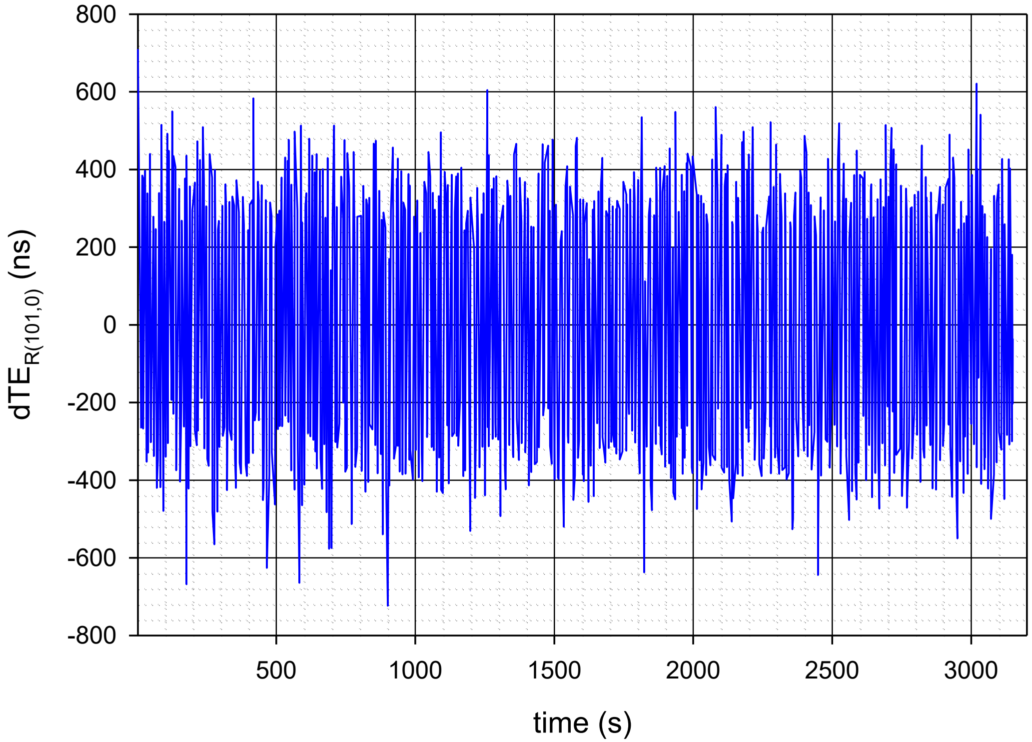
Case16, Subcase 12, Node 68 Detailed Results – 3

Subcase 12, Node 68
Replication 1: 2 - 3150 s
GM time error modeled
Clock Model (all clocks): Frequency vs temperature stability and temperature vs time profile from [3]
Accumulate neighborRateRatio, which is measured with window of size 7 and median
KpKo = 11, KiKo = 65 (f3dB = 2.6 Hz, gain pk = 1.288 dB, zeta = 0.68219)
Initial LocalClock phase waveforms chosen randomly over 100% of cycle
Residence time: 1 ms
Timestamp granularity: 8 ns
30% variation for Sync, 30% for Pdelay Intervals



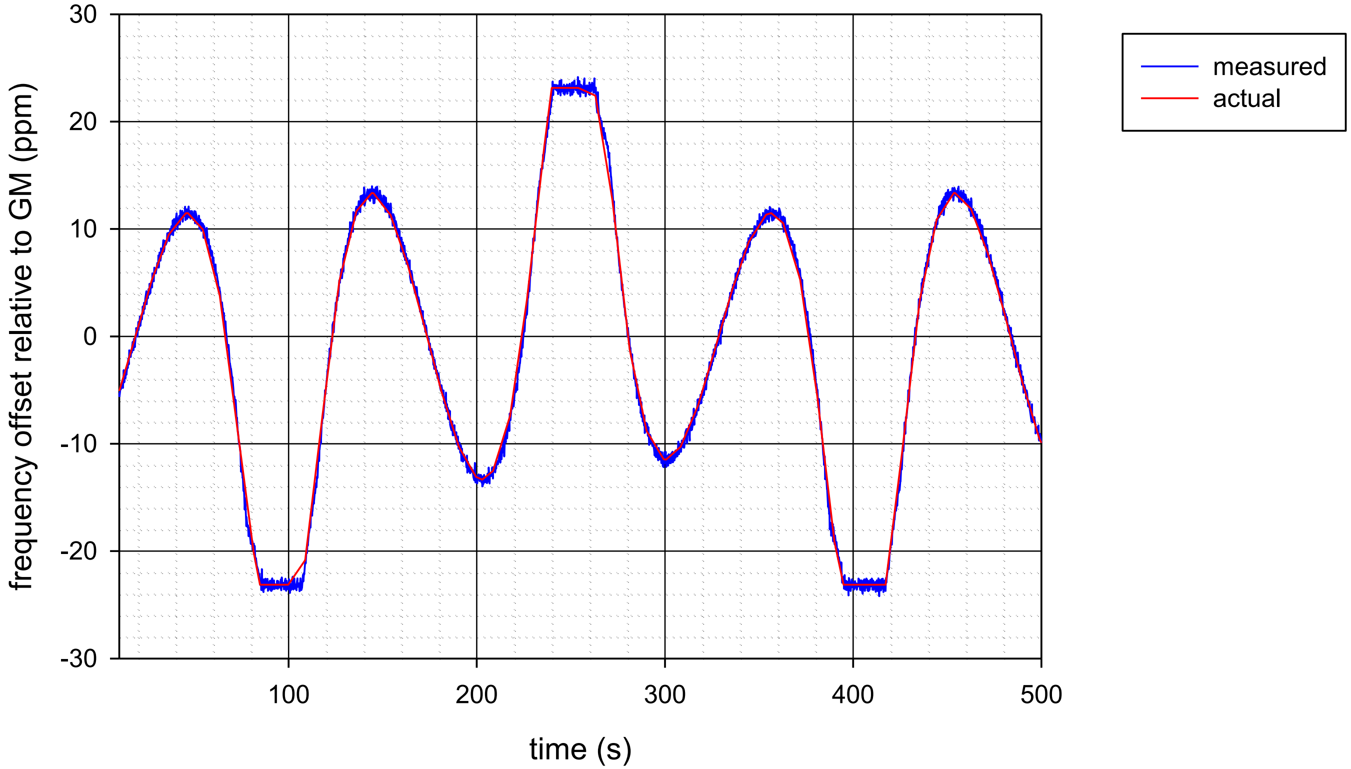
Case16, Subcase 12, Node 101 Detailed Results - 1

Subcase 12, Node 101
Replication 1: 2 - 3150 s
GM time error modeled
Clock Model (all clocks): Frequency vs temperature stability and temperature vs time profile from [3]
Accumulate neighborRateRatio, which is measured with window of size 7 and median
KpKo = 11, KiKo = 65 (f3dB = 2.6 Hz, gain pk = 1.288 dB, zeta = 0.68219)
Initial LocalClock phase waveforms chosen randomly over 100% of cycle
Residence time: 1 ms
Timestamp granularity: 8 ns
30% variation for Sync, 30% for Pdelay Intervals



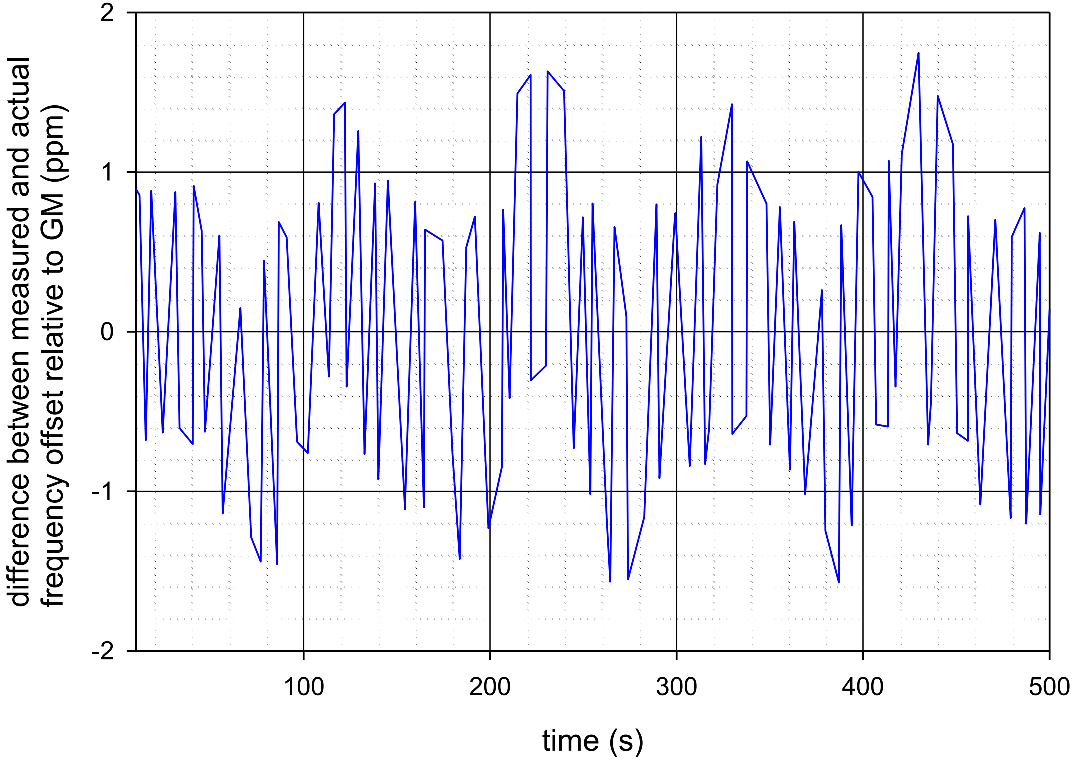
Case16, Subcase 12, Node 101 Detailed Results - 2

Subcase 12, Node 101
Replication 1: 2 - 3150 s
GM time error modeled
Clock Model (all clocks): Frequency vs temperature stability and temperature vs time profile from [3]
Accumulate neighborRateRatio, which is measured with window of size 7 and median
KpKo = 11, KiKo = 65 (f3dB = 2.6 Hz, gain pk = 1.288 dB, zeta = 0.68219)
Initial LocalClock phase waveforms chosen randomly over 100% of cycle
Residence time: 1 ms
Timestamp granularity: 8 ns
30% variation for Sync, 30% for Pdelay Intervals



Case16, Subcase 12, Node 101 Detailed Results – 3

Subcase 12, Node 101
Replication 1: 2 - 3150 s
GM time error modeled
Clock Model (all clocks): Frequency vs temperature stability and temperature vs time profile from [3]
Accumulate neighborRateRatio, which is measured with window of size 7 and median
KpKo = 11, KiKo = 65 (f3dB = 2.6 Hz, gain pk = 1.288 dB, zeta = 0.68219)
Initial LocalClock phase waveforms chosen randomly over 100% of cycle
Residence time: 1 ms
Timestamp granularity: 8 ns
30% variation for Sync, 30% for Pdelay Intervals



Subcases 3, 6, and 12, Detailed Results Summary

- Comparison of the dTE_R plots here with each other and with the dTE_R for case 16 of [1], for the same node number, indicates that differences in $\max|dTE_R|$ are due to isolated peaks (or troughs), rather than being sustained differences
- Comparison of the plots of the difference between measured and actual frequency offset relative to the GM here and for case 16 of [1] indicates some increase in frequency offset measurement error
  - However, the increases occur at isolated points in time rather than being a sustained measurement error increase
- There should be no statistically significant increase in frequency offset (relative to the GM) measurement error for cases where the Pdelay interval does not have the 30% variation, assuming all other parameters are not changed (cases 1 – 3); any difference seen is due to the fact that, with the variable Sync interval, the streams of pseudo-random numbers for the cases with and without the 30% Pdelay interval variation are different (i.e., the differences are due to statistical variability)

Conclusions - 1

- It appears that it is possible to meet the max|TE| objective of 1 μs over 64 hops, and over 100 hops if possible, if neighborRateRatio is measured over a window of size 7 or 11 (and presumably with a value in between), with the median of the 7 or 11 (or respective) values taken as the measurement, and residence time is 1 ms
- The conclusions stated in [1] (slide 73) for other parameter values are not changed):
  - If residence time is 4 ms, it might be possible to meet the max|TE| objective of 1 μs over 64 hops, but it is exceeded over 100 hops
  - Timestamp granularity is assumed to be 8 ns
    - Reducing timestamp granularity to 4 ns has small impact
  - Dynamic timestamp error is assumed to be ±8 ns, each with 0.5 probability
  - The results for 1 ms residence time appear to have sufficient margin for cTE for 64 hops; they might have sufficient margin for cTE for 100 hops, but this must be analyzed further
  - The results for 4 ms residence time might have sufficient margin for cTE for 64 hops, but this must be analyzed further

Conclusions

- max|dTE_R| results for 100 hops range from 599 ns (subcase 2) to 727 ns (subcase 6), and all results exceed the base case result of 677 ns
- Max|dTE_R| results for 64 hops range from 477 ns (subcase 2) to 727 ns (subcase 6), and all results exceed the base case result of 460 ns
- Case 6, which has both 30% Sync and Pdelay interval variation and uses a window of size 11, gives the worst results
  - Other than this, general trends cannot be discerned from single replications due to statistical variability

Possible Next Steps - Multiple Replications

- The results indicate that, to discern general trends, multiple replications of the simulations would be needed
- However, the long run times required make it impractical to run 300 multiple replications for all 12 subcases
- In [1], multiple replications were run for 4 simulation cases (cases 16, 18, 22, and 27)
  - 4 cases were selected because the processor of the machine used for simulations has four cores
- It is suggested that, if multiple replication runs are desired, four of the subcases be chosen
  - An initial suggested is to run multiple replications for subcases 3, 4, 6, 12

Possible Next Steps - Consideration of cTE

- This slide is repeated from [1]
- Whether there is sufficient margin for cTE depends on how much cTE is allocated per gPTP link (including the effect of both the node and medium), and the model for accumulating cTE
  - See [10] for an initial analysis
- One next step is to consider cTE and any other impairments (e.g., effect of network reconfiguration), and develop an error budget
- A future presentation can consider this

Possible Next Steps - Consideration of Requirements and Compliance - 1

- This slide and the next are repeated from [1]; they contain some initial ideas on what can be specified and how compliance can be tested
- The model for measurement of neighborRateRatio based on a window of size 7 and computation of the median is one of many ways that neighborRateRatio can be measured
- The particular way in which it is measured is implementation specific
- The IEC/IEEE 60802 profile should allow any measurement scheme, as long as respective requirements are met
  - In the case here, the requirement is that the error in the measurement of neighbor frequency offset (i.e., neighborRateRatio – 1) not exceed a specified limit
  - The results here indicate that the limit of 802.1AS-2020, B.2.4, of ±0.1 ppm will give acceptable results because the results obtained in cases 16, 18, and 22 had maximum neighbor frequency offset error of 0.56 ppm with no GM time error variation (obtained in [1]) and 0.72 ppm with the GM time error variation considered here
  - Therefore, the limit could be larger than 0.1 ppm, but will depend on how compliance is tested (e.g., with or without GM time error variation)

Possible Next Steps - Consideration of Requirements and Compliance - 2

- Since the Follow_Up Information TLV carries accumulated rateRatio, it should be possible to test a single PTP Instance with a test set both serving as the GM and measuring the result
- Limits on timestamp granularity and dynamic timestamp error also are relevant
  - These are tolerance requirements when the accuracy of the neighborRateRatio measurement is tested
  - In such a test, the test set would need to add both the specified timestamp granularity and dynamic timestamp error to the PTP event messages sent to the equipment under test, because the scheme used in the neighborRateRatio measurement would need to tolerate these errors
  - However, there would be no explicit requirement on timestamp granularity or dynamic timestamp error for the equipment under test itself
    - Rather, any timestamp granularity, dynamic timestamp error, and method for measuring neighborRateRatio would be allowed as long as the error in measured neighborRateRatio did not exceed the specified limit
- A more detailed description of these considerations can be given in a future presentation

Thank you

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[1] Geoffrey M. Garner, *New Simulation Results for dTE for an IEC/IEEE 60802 , Based on New Frequency Stability Model, Version (Revision) 1*, IEC/IEEE 60802 presentation, May 3, 2021 (available at https://www.ieee802.org/1/files/public/docs2021/60802-garner-multipe-replic-simulation-results-new-freq-stab-model-0421-v01.pdf)

[2] Geoffrey M. Garner, *New Simulation Results for dTE for an IEC/IEEE 60802 , Based on New Frequency Stability Model, Revision 1*, IEC/IEEE 60802 presentation, April 9, 2021 (available at https://www.ieee802.org/1/files/public/docs2021/60802-garner-new-simulation-results-new-freq-stab-model-0421-v01.pdf)

[3] Geoffrey M. Garner, *Summary of Assumptions for Next Simulations, based on Presentation and Subsequent Discussion of [1], Revision 1*, IEC/IEEE 60802 presentation, March 11, 2021 (available at https://www.ieee802.org/1/files/public/docs2021/60802-garner-summary-of-assumptions-next-simulations-0321-v01.pdf)

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[4] Chris McCormick, *Crystal Fundamentals & State of the Industry*, IEC/IEEE 60802 presentation, February 22, 2021 call (available at https://www.ieee802.org/1/files/public/docs2021/60802-McCormick-Osc-Stability-0221-v01.pdf)

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[7] ITU-T Series G Supplement 65, *Simulations of transport of time over packet networks*, Geneva, October 2018

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[8] Milton Abramowitz and Irene A. Stegun, *Handbook of Mathematical Functions with Formulas, Graphs, and Mathematical Tables*, National Bureau of Standards, Applied Mathematics Series 55, June 1964 (Tenth Printing, December 1927, with corrections).

[9] Geoffrey M. Garner, *Further Simulation Results for Dynamic Time Error Performance for Transport over an IEC/IEEE 60802 Network Based on Updated Assumptions*, Revision 2, December 14, 2020 call (available at https://www.ieee802.org/1/files/public/docs2020/60802-garner-further-simulation-results-time-sync-transport-1120-v02.pdf)

[10] Geoffrey M. Garner, *Analysis of the Accumulation of Constant Time Error in an IEC/IEEE 60802 Network*, IEC/IEEE 60802 presentation, March 16, 2020 (available at https://www.ieee802.org/1/files/public/docs2020/60802-garner-analysis-of-accum-of-cTE-in-60802-network-0320-v00.pdf)