Further 60802 Error Generation Time Series Simulation Results Version 2

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Introduction - 1

- This Introduction is adapted from the Introduction of [8]
- Tables 13 and 14 of IEC/IEEE 60802/D2.2 [1] contain error generation limits for a PTP Relay Instance and a PTP End Instance, respectively
- Annex D, Subclause D.4, of 60802 describes an approach to testing these requirements
  - While D.4 is informative and is not a test specification, it provides sufficient information to enable simulations of possible test setups to be performed, to see whether meeting the error generation limits is reasonable
  - D.4 is based on [2] ([2] was used in preparing [8] because, at that time, only 60802/D1.1 was available; figure and table numbers are based on [1])
- In [3], Monte Carlo simulation results are given for the error generation tests of D.4 for a PTP Relay Instance, and compare results for cases with and without the use of drift tracking and compensation algorithms
  - The results in [3] (see slide 16) meet the requirements of Table 12 of [1]

Introduction - 2

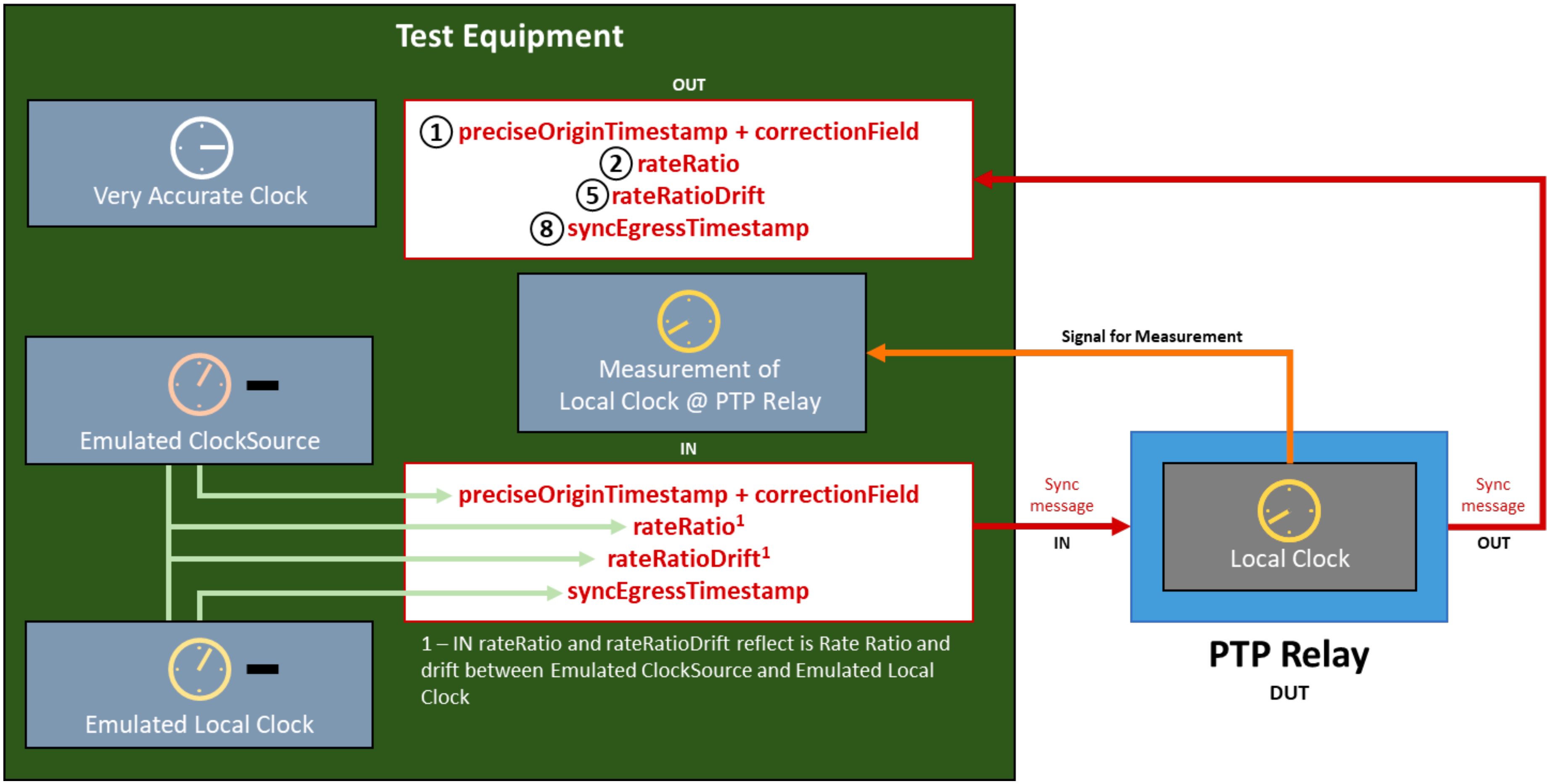
- One of the next steps described in [3] is to run time series simulations for the test cases of Annex D of [1], for both PTP Relay Instances and PTP End Instances
  - Time series simulations are needed for PTP End instances in particular because dTE results End Instances are after any endpoint filtering
- Initial time series (i.e., time domain) simulation results were run and given in [8]
  - Some of the results did not meet the 60802 Table 13 and 14 error generation limits
  - Discussion at the January 2024 802.1 interim session indicated that some of the assumptions for the simulations needed to be modified
  - Reference [9] was prepared to document the modified assumptions
- The current presentation describes the updated time series simulation results, based on assumptions of [9]
- These results are based on multiple replications of each simulation case

Description of Test Setup and Model for Simulator - 1

- This slide, and the following four slides, are taken from [8]; they are reproduced here for convenience
- A possible setup for testing a PTP Relay Instance is shown in Figures D.2, D.3, and D.4 of [1] and [2]
- A possible setup for testing a PTP End Instance is shown in Figure D.5 of [1] and [2]
- For convenience, Figures D.2 and D.5 of [1] and [2] are reproduced on the next slide (Figures D.3 and D.4 differ from D.2 only on that the three figures label different outputs for the different tests)
- In the time series simulator, the ClockSource and LocalClock at the Grandmaster (GM) PTP Instance are the same clock, while in Annex D.4 they are different clocks
- Therefore, the Emulated ClockSource and Emulated LocalClock of Figures D.2 and D.5 of [1] and [2] must be modeled as two separate nodes in the time series simulator
- In addition, since the test cases require the values of fields sent in the Sync/Follow_Up messages of the device under test (DUT), a node that follows the DUT is needed in the time series simulation model

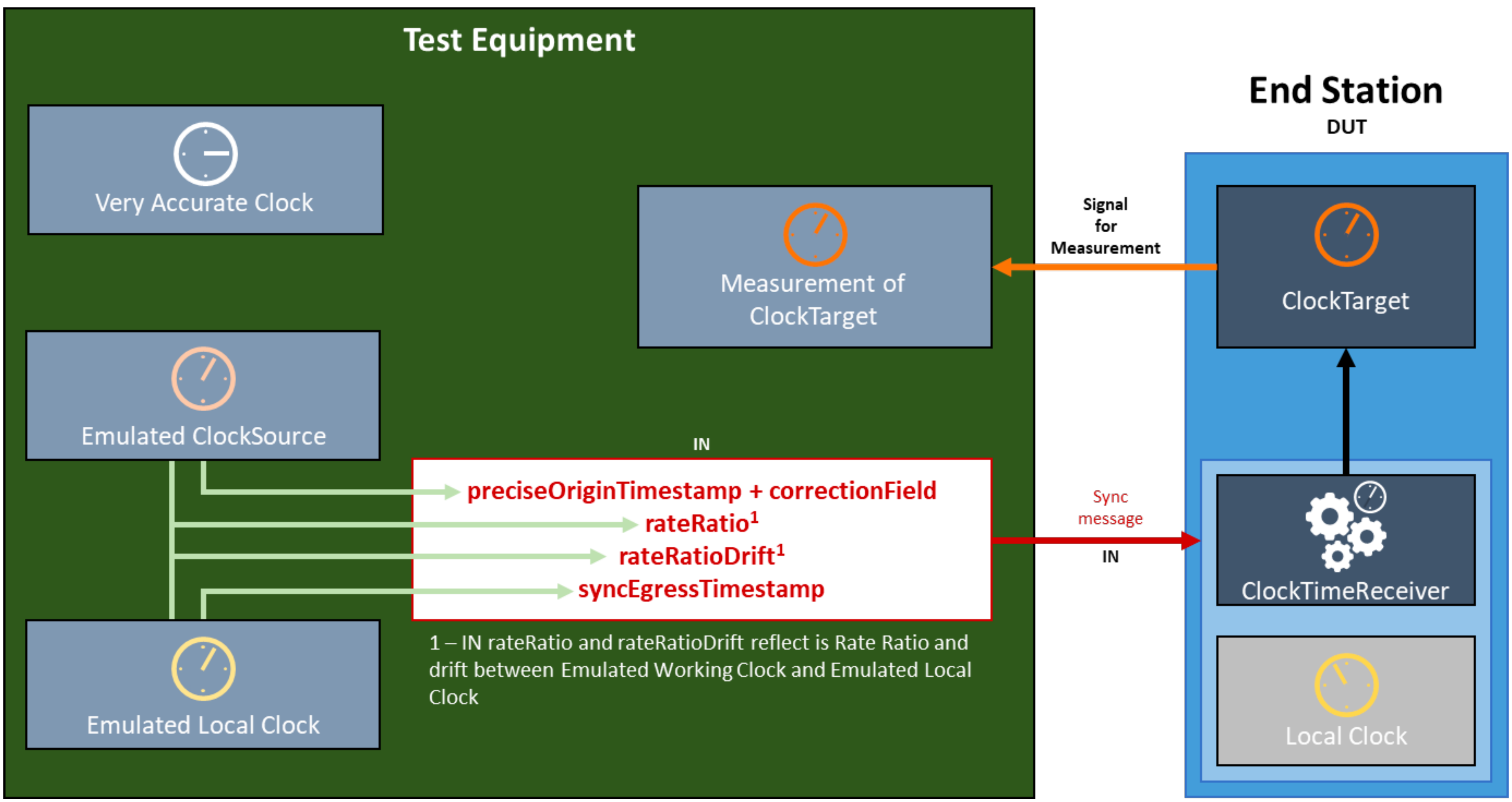
Description of Test Setup and Model for Simulator - 2

- Figure D.2 of [1] and [2] – possible test setup for PTP Relay Instance



Description of Test Setup and Model for Simulator - 3

- Figure D.5 of [1] and [2] – possible test setup for PTP End Instance

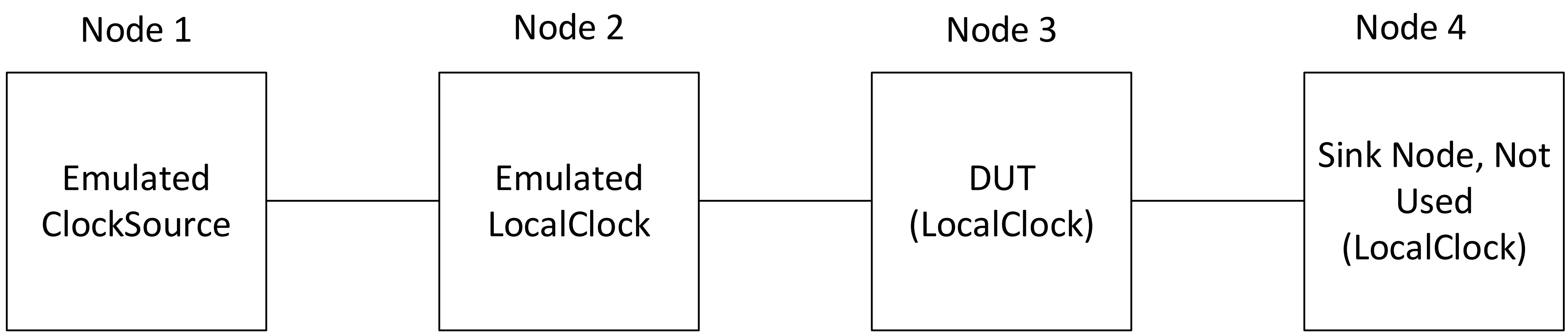


Description of Test Setup and Model for Simulator - 4

- The above means that the time series simulation model has four nodes:
  - Node 1 – Emulated ClockSource
  - Node 2 – Emulated LocalClock
  - Node 3 – DUT
  - Node 4 – Sink node that receives messages sent by the DUT
- A schematic of the simulator model is shown on the next slide
  - For convenience, these nodes are referred to by node number in the remainder of this presentation
- For the PTP Relay Instance tests, node 4 is not used; the tests only need values of fields of the Sync message (the time series simulator does not model two-step behavior explicitly) sent by the DUT
- For the PTP End Instance only filtered dTE is needed (see Table 14 of [1]), and this is the filtered dTE of the DUT (node 3)
  - Since both filtered and unfiltered dTE results are produced at each node, the same simulation runs can cover the PTP Relay Instance and PTP End Instance cases

Description of Test Setup and Model for Simulator - 5

Schematic of Time Domain Simulation Model



Assumptions Common to All Simulation Cases - 1

- The assumptions and endpoint filter slides are taken from [8], but with modifications for the revised assumptions described in [9]
- The timestamp granularity is assumed to be 8 ns, based on a 125 MHz clock
  - The timestamp is truncated to the next lower multiple of 8 ns
  - This error is present only at node 3 (DUT); it is zero at other nodes
- The dynamic timestamp error is assumed to be uniformly distributed over [-6 ns, +6 ns]
  - This error is present only at node 3; it is zero at other nodes
- Pdelay Interval
  - Pdelay is used only to compute meanLinkDelay, and not neighborRateRatio (NRR)
  - NRR is computed using successive Sync message (using the syncEgressTimestamp)
  - The nominal Pdelay interval is 125 ms
  - The actual Pdelay interval is assumed to be uniformly distributed in the range [(0.9)(125 ms), (1.3)(125 ms)] = [112.5 ms, 162.5 ms]

Assumptions Common to All Simulation Cases - 2

❑Sync Interval

- The Sync interval is assumed to be uniformly distributed in the range [119 ms, 131 ms]

❑Residence time

- The residence time is assumed to be a truncated normal distribution with mean of 5 ms and standard deviation of 1.8 ms, truncated at 1 ms and 15 ms
- Probability mass greater than 15 ms and less than 1 ms is assumed to be concentrated at 15 ms and 1 ms, respectively (i.e., truncated values are converted to 15 ms or 1 ms, respectively)
- Residence time at node 1 (GM) is irrelevant
- Residence time at node 2 is 0 ns
- Residence time is present at node 3 (and is given by the first two sub-bullets above)
- Residence time at node 4 is irrelevant

Assumptions Common to All Simulation Cases - 3

❑Pdelay Turnaround Time

- The Pdelay turnaround time is assumed to be a truncated normal distribution with mean of 10 ms and standard deviation of 1.8 ms, truncated at 1 ms and 15 ms
- Probability mass greater than 15 ms and less than 1 ms is assumed to be concentrated at 15 ms and 1 ms, respectively (i.e., truncated values are converted to 15 ms or 1 ms, respectively)
- Pdelay turnaround time is 0 ns at node 1 (GM)
- Pdelay turnaround time is present at node 2, and is given by the first two sub-bullets above
- Pdelay turnaround time irrelevant at nodes 3 and 4

Assumptions Common to All Simulation Cases - 4

❑Link Delay

- Link delay is assumed to be uniformly distributed between 5 ns and 500 ns
- Link delays are generated randomly at initialization and kept at those values for the entire simulation
- Link asymmetry is not modeled
- For the single replication simulation cases here, link delay is
  - 0 ns for the link between nodes 1 and 2
  - 454.21 ns for the link between nodes 2 and 3
  - Irrelevant for the link between nodes 3 and 4

Assumptions Common to All Simulation Cases - 5

❑Mean Link Delay Averaging

- Mean link delay averaging is as described in D.5.7 of [1] and [2]
- The very first mean link delay measurement (made using the peer delay mechanism) is taken as the measured value, x_1
- For subsequent measurements up to 1000 measurements, the averaging filter is given by

$$y_k = \frac{(k-1)y_{k-1} + x_k}{k}$$

- where y_k is the k^{th} filter output and x_k is the k^{th} measurement, with $2 \le k \le 1000$
- For measurements after 1000 measurements ($k > 1000$), the averaging filter is given by

$$y_k = a_1 y_{k-1} + b_0 x_k$$

- where $a_1 = 0.999$, and $b_0 = 0.001$

Assumptions Common to All Simulation Cases - 6

- Mean Link Delay Averaging (cont.)
  - For $k > 1000$, the averaging function is an IIR filter that uses 0.999 of the previously computed value and 0.001 of the most recent measurement
  - This is equivalent to the filter of the NOTE of B.4 of 802.1AS-2020, taken as a first-order filter
- For simulation cases with no clock drift, the first 500 s of data is removed when statistics over time are computed, so that any initial transient due to the averaging filter output has decayed
- For simulation cases with clock drift, the clock drift is present between 1000 s and 1200 s, and statistics over time are computed for data between 1005 s and 1200 s (to remove the effect of transients caused by the abrupt starting and stopping of the clock drift)
  - The removal of the first 1005 s when computing statistics removes the effect of any initial transient due to the averaging filter

Assumptions Common to All Simulation Cases - 7

❑Clock drift

- In all cases, node 3 (DUT) is assumed to have a stable LocalClock, i.e., its clock drift is zero
- Clock drift is present in nodes 1 and 2 in some of the cases (the specific cases are described in detail later)
- Clock drift, when present, is as follows:
  - The clock frequency is stable at -100 ppm (relative to nominal) from initialization to 1000 s
  - The clock frequency then drifts from -100 ppm to +100ppm at a rate of 1 ppm/s (i.e., over 200 s), to time 1200 s
  - The clock frequency is constant at +100 ppm from 1200 s until the end of the simulation time
    - Note: In initial discussions, it was indicated that the clock drift of 1 ppm/s would begin after 100 s; however, it was found that more time was needed for the initial transient, due to starting the simulation with non-zero frequency offset, to decay away. An initialization time of 1000 s was chosen as a conservative value after which the transient has decayed.

Assumptions Common to All Simulation Cases - 8

- Drift tracking and compensation algorithms are used in all cases at nodes 1, 2, and 3, and are as described in [1] and [2]
  - The algorithms are irrelevant at node 4
- Unlike previous simulation cases (e.g., see [4] and [8]), drift tracking and compensation for the PTP End Instance is modeled (the algorithms are applied when computing the input to the endpoint filter)
- All the simulation cases here use (see [1] – [4], and references cited in those presentations, for details):
  - mNRRcompNAP = 8; mNRRsmoothingNA = 4

Endpoint filter (PLL) Parameters – 1

- Simulation results presented in [4] indicated that the endpoint filter needs to have a 3 dB bandwidth in the range 0.7 Hz to 1 Hz and a maximum gain peaking of 2.1985 dB
- For the simulation cases here, the 3 dB bandwidth is assumed to be 1 Hz, and the gain peaking is assumed to be 2.1985 dB
  - The corresponding undamped natural frequency is 3.1011 rad/s
- The PLL model used in the simulator is second-order and linear, with 20 dB/decade roll-off
  - It is based on a discretization that uses an analytically exact integrating factor to integrate the second-order system
  - As a result, the PLL model in the simulator is stable regardless of the time step, i.e., sampling rate (though aliasing of the input or noise is possible)
  - Details are given in Appendix VIII.2.2 of [5] (except that the relation between gain peaking and damping ratio is based on the exact result in 8.2.3 of [6] (see Eqs. (8-13 – 8-15 there)

Endpoint filter (PLL) Parameters - 2

❑PLL noise generation (Cont.)

- PLL noise generation is modeled as described in [4], i.e., using the same local oscillator phase variation model used for the LocalClock
- The noise is computed by passing the XO phase noise through a high-pass filter with the same 3dB bandwidth and damping ratio as the low-pass PLL filter, and adding the result to the PLL output that was computed from the input
- However, the PLL is associated with the PTP End Instance, i.e., the DUT, and it was indicated in the assumptions related to clock drift that the DUT is assumed to have a stable LocalClock, i.e., its clock drift is assumed to be zero
- **This means that the PTP End Instance endpoint filter is assumed to have zero noise generation**

Endpoint filter (PLL) Parameters – 3

❑PLL noise generation (Cont.)

- Since the DUT drift is emulated by applying drift to the Emulated LocalClock, this is equivalent to assuming that the actual clock drift of the DUT is zero
- **At the very least, this means the actual tests should be done at constant temperature**
- This means that the actual DUT noise generation when the test is performed is the noise generation at constant temperature
- **The underlying assumption is that the DUT noise generation at constant temperature is negligible compared to the PTP End Instance requirement on filtered dTE**
- Note that in the time series simulations for a chain of PTP Instances [4], temperature was assumed to be varying according to the given temperature profile

Summary of Simulation Cases

- In what follows (and in [9]), the terms “case” and “experiment” are used interchangeably (except that experiment 1 includes cases 1, 1b, and 1c)
- In all cases, the node 3 local clock has 0 ppm offset and no clock drift
- In all cases, the node 4 clock offset and drift are irrelevant
- The numbering of the cases (1, 1b, 1c, 2, and 4) is taken from [9] (case 4 is a new case added here, i.e., it is not described in [9])
- For cases 1, 2, 3, and 4, clock drift, when present, is as described in Assumptions slide 7
- The details of Experiment 1, Data analyses 1, 2, and 3, and Experiments 2 and 3, are described in [9]

Summary of Simulation Cases - 1

Case	Simulation Time (s)	Number of Independent Replications	Clock Offset and Drift at Node 1	Clock Offset and Drift at Node 2	Interval over which statistics are computed
1	100500	300	No	No	500 – 10000 s
1b	100500	300	No	+1 ppm offset, no drift	500 – 10000 s
1c	100500	300	No	Sinusoidal offset; $\pm$1 ppm amplitude and 10 s period	500 – 10000 s
2	2000	1000	Yes	No	1005 – 1200 s
3	2000	1000	Yes	Yes	1005 – 1200 s
4	2000	1000	No	Yes	1005 – 1200 s

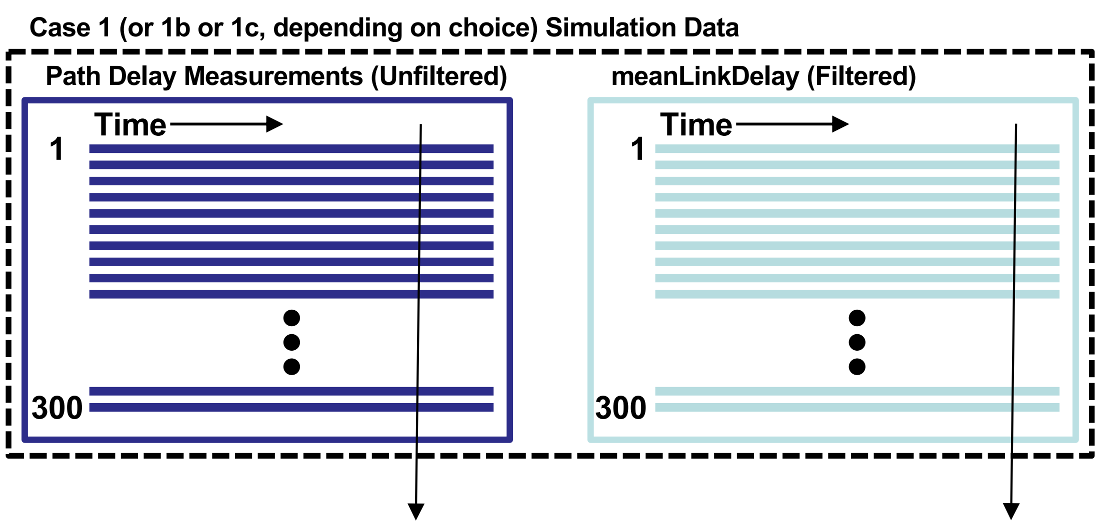
Clock offset and drift in cases 2, 3, and 4 is as described above in Assumptions slide 7

Outputs of Interest

- Measured mean link delay by node 3, for link between nodes 2 and 3, after averaging filter
- Measured path delay by node 3, for link between nodes 2 and 3, before averaging filter
- preciseOriginTimestamp + correctionField – (Working Clock at GM), at node 3, when Sync is sent by node 3
- rateRatio field of Sync message minus actual rateRatio, at node 3, when Sync is sent by node 3
- rateRatioDrift field of Drift_Tracking TLV minus actual rate ratio drift, at node 3, when Sync is sent by node 3
- Filtered dTE at node 3

Experiment 1, Data Analysis 1 and Part of 2 - 1

- Data analysis 1 and part of data analysis 2, as described in [9], with some additional results
- Sample mean μ and sample standard deviation σ are computed over the 300 replications (i.e., ensemble averages), at each point in time (see figure below, which is a minor modification of one of the figures supplied in [10])



Compute μ and σ over th
e 300 replications, at eac
h
sample time point

Compute μ and σ over th
e 300 replications, at eac
h
sample time point

Experiment 1, Data Analysis 1 and Part of 2 - 2

- The following plots are generated, for each of cases 1, 1b, and 1c (8 plots for each case)
  - Mean link delay after IIR filtering – replication 1
  - Mean link delay after IIR filtering – replication 300
  - Mean link delay before IIR filtering – replication 1
  - Mean link delay before IIR filtering – replication 300
  - For link delay: Mean, mean+6σ, mean-6σ, after IIR filtering, across 300 replications, as a function of time
  - For link delay: Mean, mean+6σ, mean-6σ, before IIR filtering, across 300 replications, as a function of time
  - For link delay: Standard deviation after IIR filtering, across 300 replications, as a function of time
  - For link delay: Standard deviation before IIR filtering, across 300 replications, as a function of time

Experiment 1, Data Analysis 1 and Part of 2 - 3

- This slide and the next 3 slides are taken from [8], with some minor modifications
- The results have the same behavior as the mean link delay results in [8]
- The unfiltered results show fast variation due to the $\pm$6 ns dynamic timestamp error
- The 8 ns timestamp granularity, but without link delay averaging, results in relatively infrequent jumps (i.e., over periods of thousands of seconds) of approximately 4 ns, plus some jumps that are less than 4 ns
- The averaging filter reduces the $\pm$6 ns fast variation; however, the infrequent jumps remain

Experiment 1, Data Analysis 1 and Part of 2 - 4

- The infrequent jumps in measured link delay are caused by the truncation due to timestamp granularity
  - Note that there is timestamp granularity error and dynamic timestamp error only at the DUT, which means that there are sources of these errors in the peer delay computation on the DUT’s upstream link, one truncation when timestamping the transmitted Pdelay_Req, and one truncation when timestamping the received Pdelay_Resp
  - Note also that, if 4 ns were added to these timestamps, the effect of that would cancel; the variation in these results is ***not*** due to not adding the 4 ns
  - If one Pdelay_Req message has a timestamp truncated by almost 8 ns, and the associated Pdelay_Resp message has truncation close to zero, the result is a 4 ns error in measured link delay (without averaging), due to the division by 2 in the computation
  - Similarly, if a Pdelay_Resp timestamp is truncated and the corresponding Pdelay_Req timestamp is not truncated, the result is a -4ns error in measured mean link delay
  - However, these truncations are relatively infrequent, and most of the time both truncations do not occur in the same peer delay exchange; this results in a shift of the pattern by approximately 4 ns

Experiment 1, Data Analysis 1 and Part of 2 - 5

- The actual link delay is 454.21 ns; much of the variation is centered on this value, but sometimes it is shifted by -4 ns (and it is centered on this value for the cases where timestamp granularity is set to zero)
- Note that there is not a regular, low-frequency, beating pattern because the send and receive timestamps are not being taken at fixed frequencies that differ by a small amount; rather, Pdelay_Req is being sent at intervals that have some random variation (which results in truncation being different on successive peer delay message exchanges)
  - Also, there is additional randomness due to the nonzero pdelay turnaround time at node 2

Experiment 1, Data Analysis 1 and Part of 2 - 6

- The mean link delay averaging uses a window of 1000 peer delay exchanges
  - The Pdelay interval varies uniformly from 112.5 ms to 162.5 ms; the mean of this distribution is137.5 ms, which means that 1000 exchanges would occur over an interval of 137.5 s on average
  - This means that the time constant of the averaging filter is on the order of hundreds of seconds
  - The averaging filter removes the fast variation in the measurement, but requires a few hundred seconds to respond to an isolated jump in the pattern
  - In addition, if the pattern jumps and then jumps back before the filter has fully responded, the result is a smaller amplitude change in the pattern (as seen in the result with the averaging filter around 2400 s for case 1, replication 1)

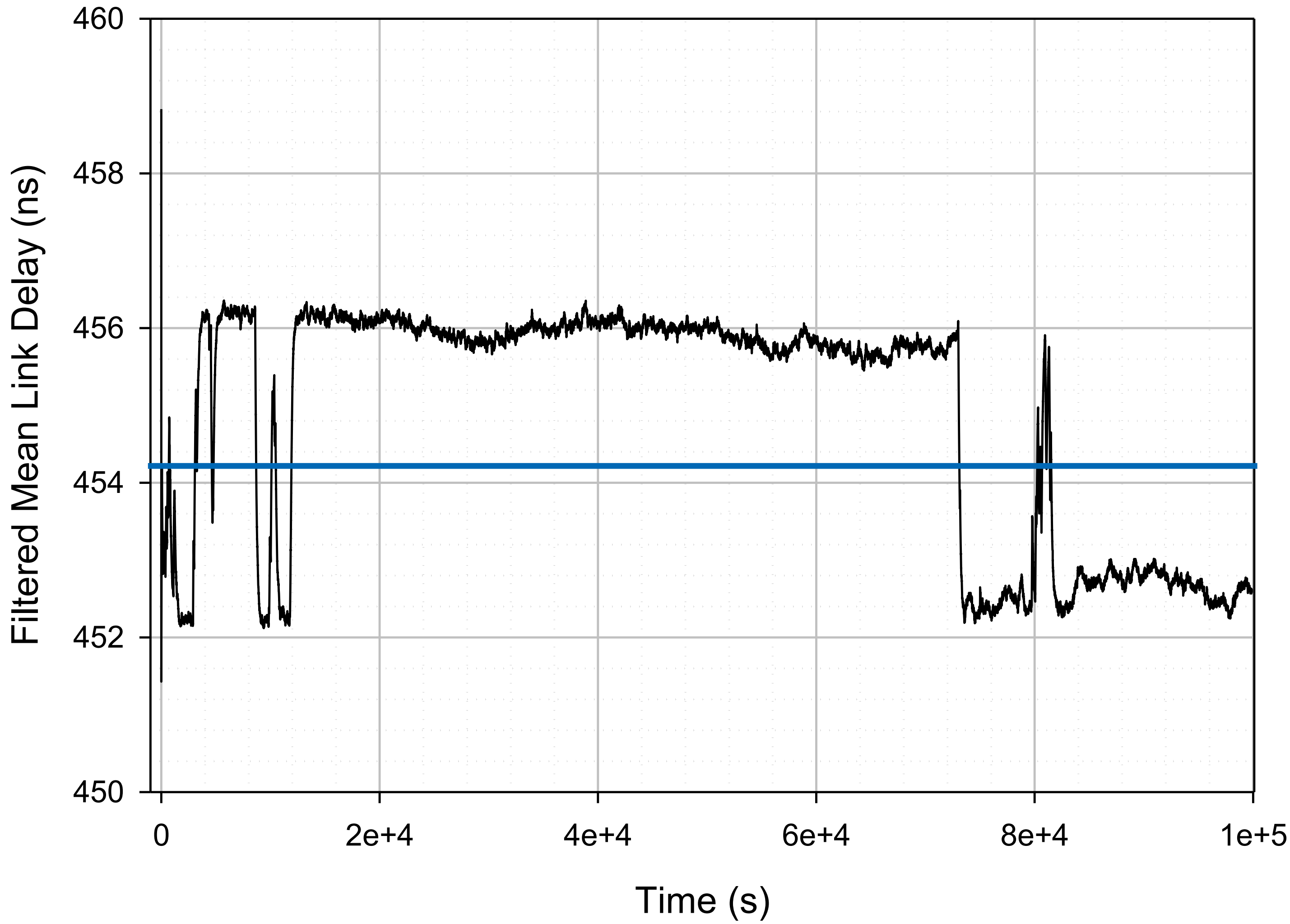
Experiment 1, Data Analysis 1 and Part of 2 - 7

- The mean link delays for cases 1, 1b, and 1c are qualitatively very similar (i.e., the filtered and unfiltered time histories for all three cases show the behavior described in four slides)
- The mean of the filtered mean link delay, averaged over the 300 replications, is almost identical for cases 1, 1b, and 1c (compare slides 37, 48, and 59)
- The mean of the unfiltered mean link delay, averaged over the 300 replications, is very similar for cases 1 and 1b, but shows somewhat more variability for case 1c (compare slides 38, 49, and 60)
- The standard deviation of the filtered mean link delay, averaged over the 300 replications, is very similar for cases 1, 1b, and 1c (compare slides 39, 50, and 61)
- The standard deviation of the unfiltered mean link delay, averaged over the 300 replications, appears to be similar for cases 1, 1b, and 1c (compare slides 40, 51, and 62)
    - This might seem inconsistent with the larger variability of the mean for case 1c; however, the variability in the mean for case 1c is larger than for cases 1 and 1b by 2 – 4 ns, while the range of the standard deviation estimate is 8 ns; a better estimate of the standard deviation is needed to determine the consistency of the mean and standard deviation for case 1c

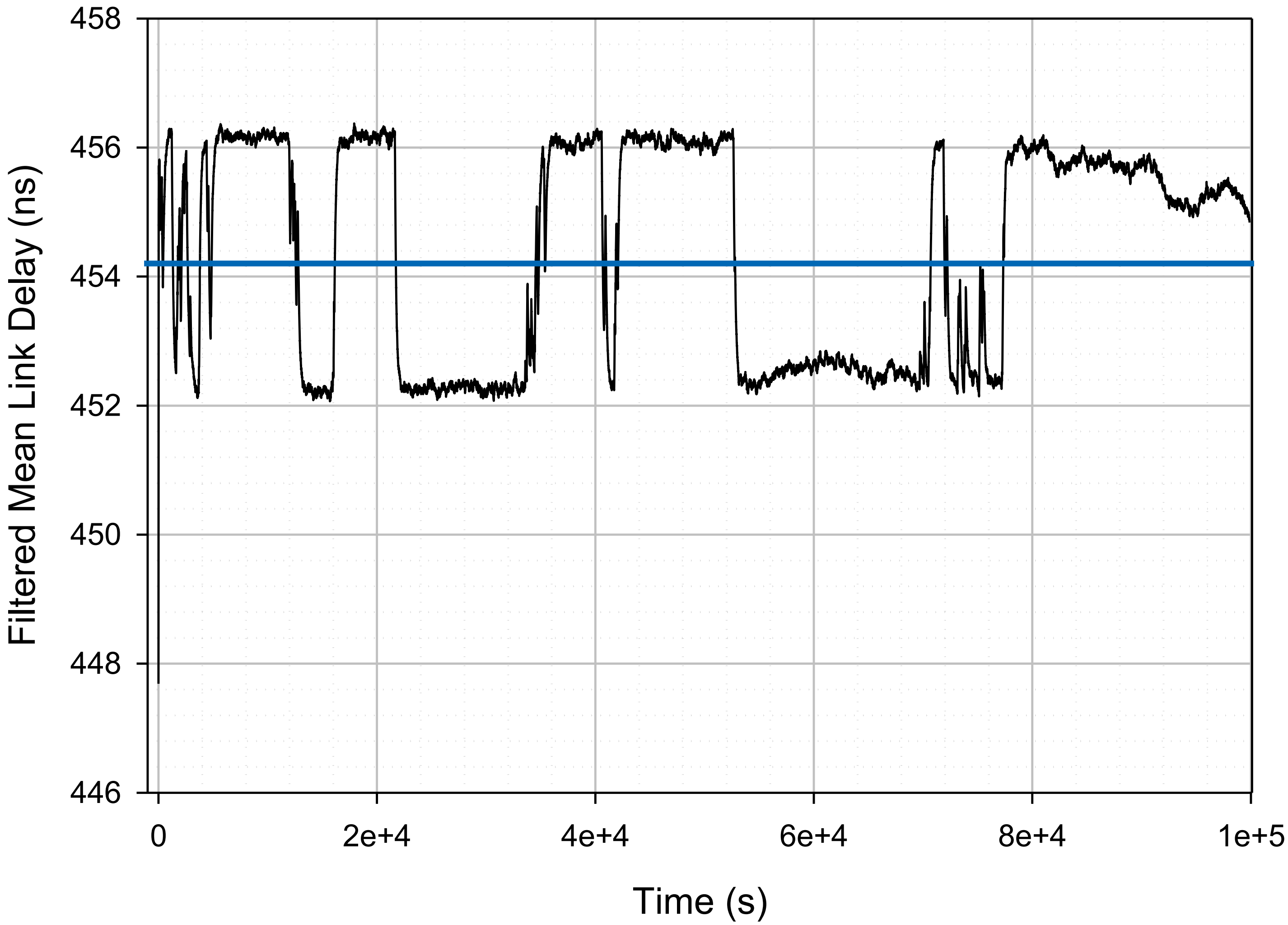
Results for Case 1 – following 10 slides

- The scatter plots on slides 34 and 36, and the average level indications, were supplied by David McCall, March 2024.

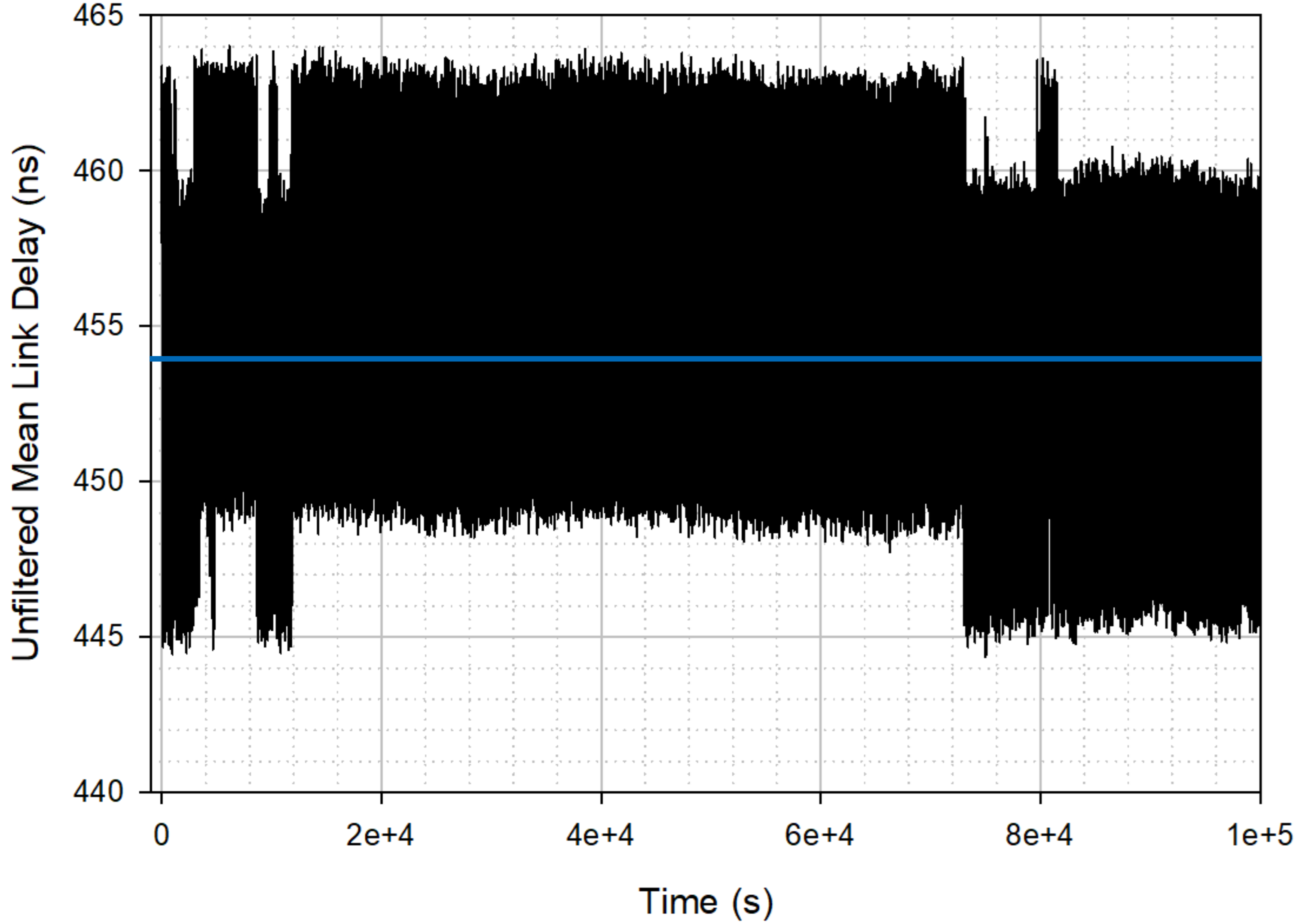
Case01 - Mean Link Delay after IIR Filtering - Replication 1

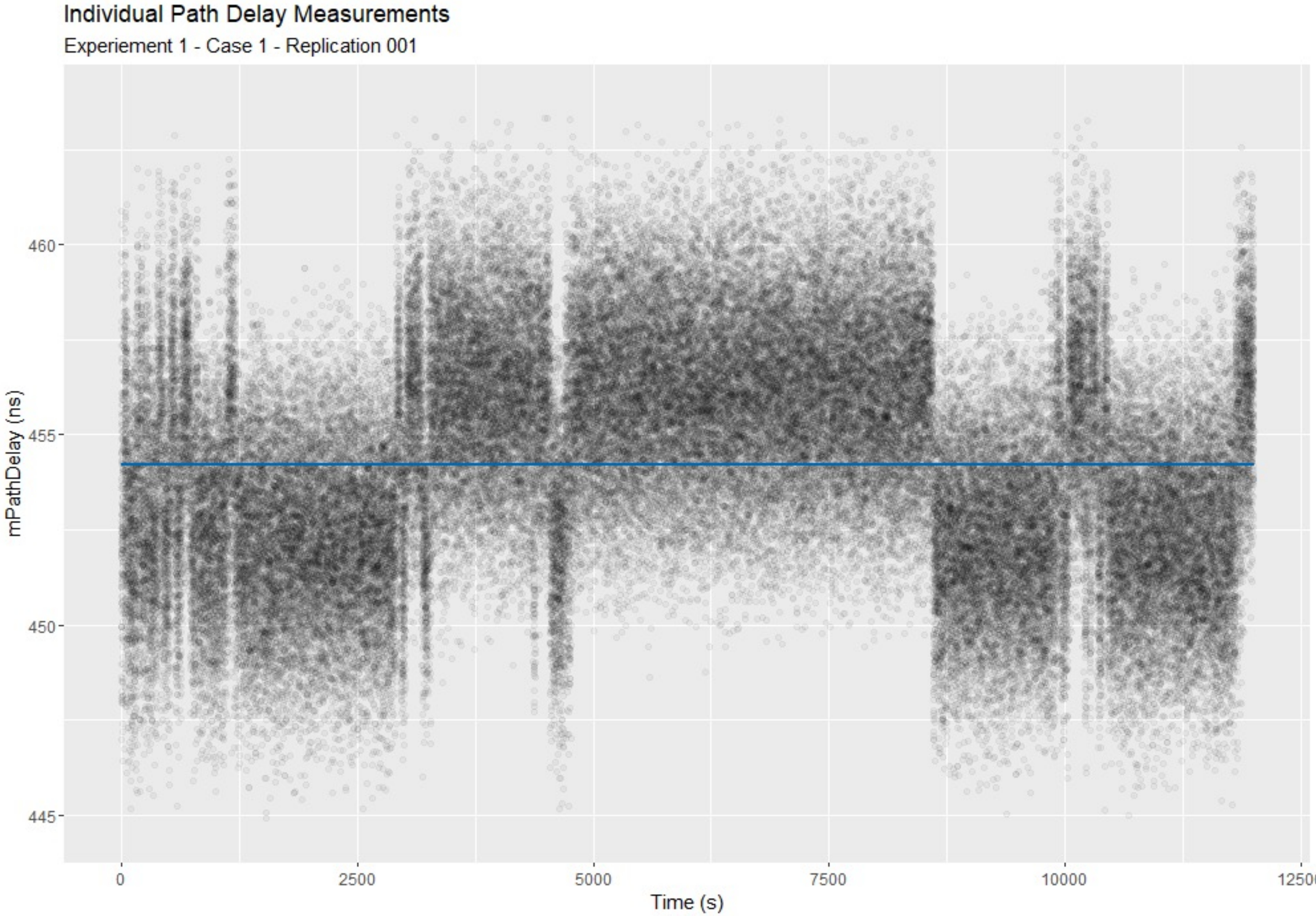


Case01 - Mean Link Delay after IIR Filtering - Replication 300

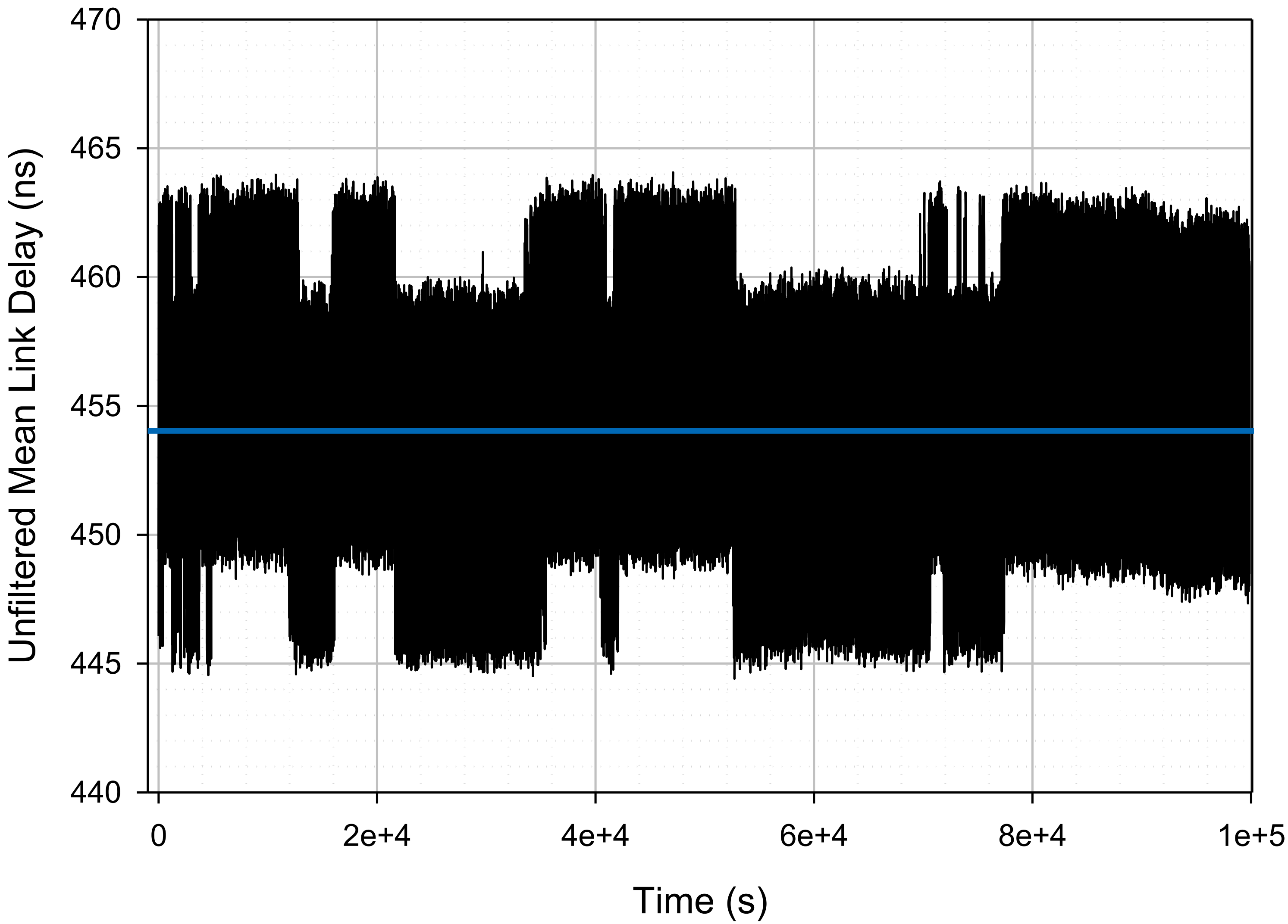


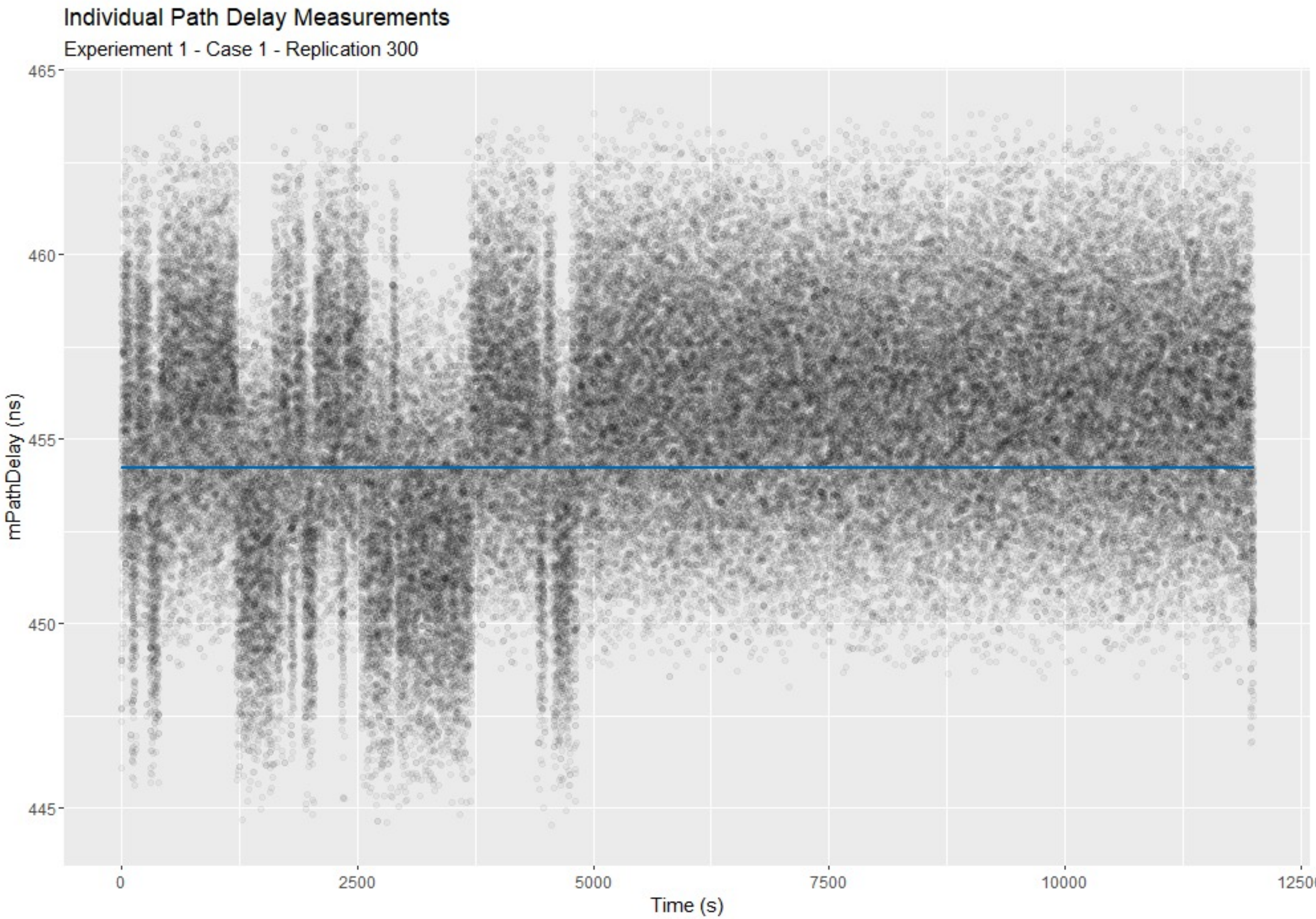
Case01 - Mean Link Delay before IIR Filtering - Replication 1



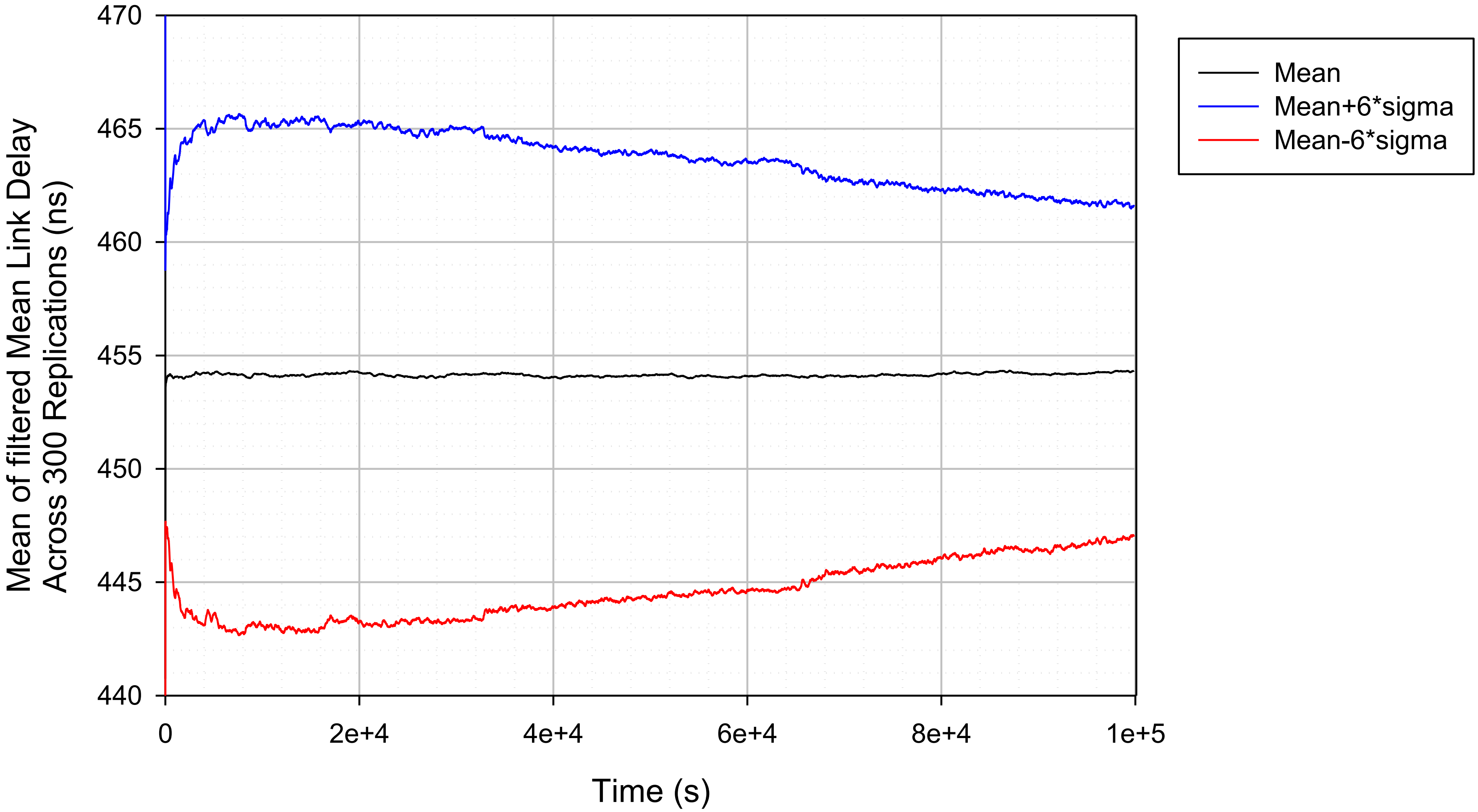

Individual Path Delay Measurements
Experiement 1 - Case 1 - Replication 001
mPathDelay (ns)
460
455
450
445
0
2500
5000
7500
10000
12500
Time (s)

Case01 - Mean Link Delay before IIR Filtering - Replication 300

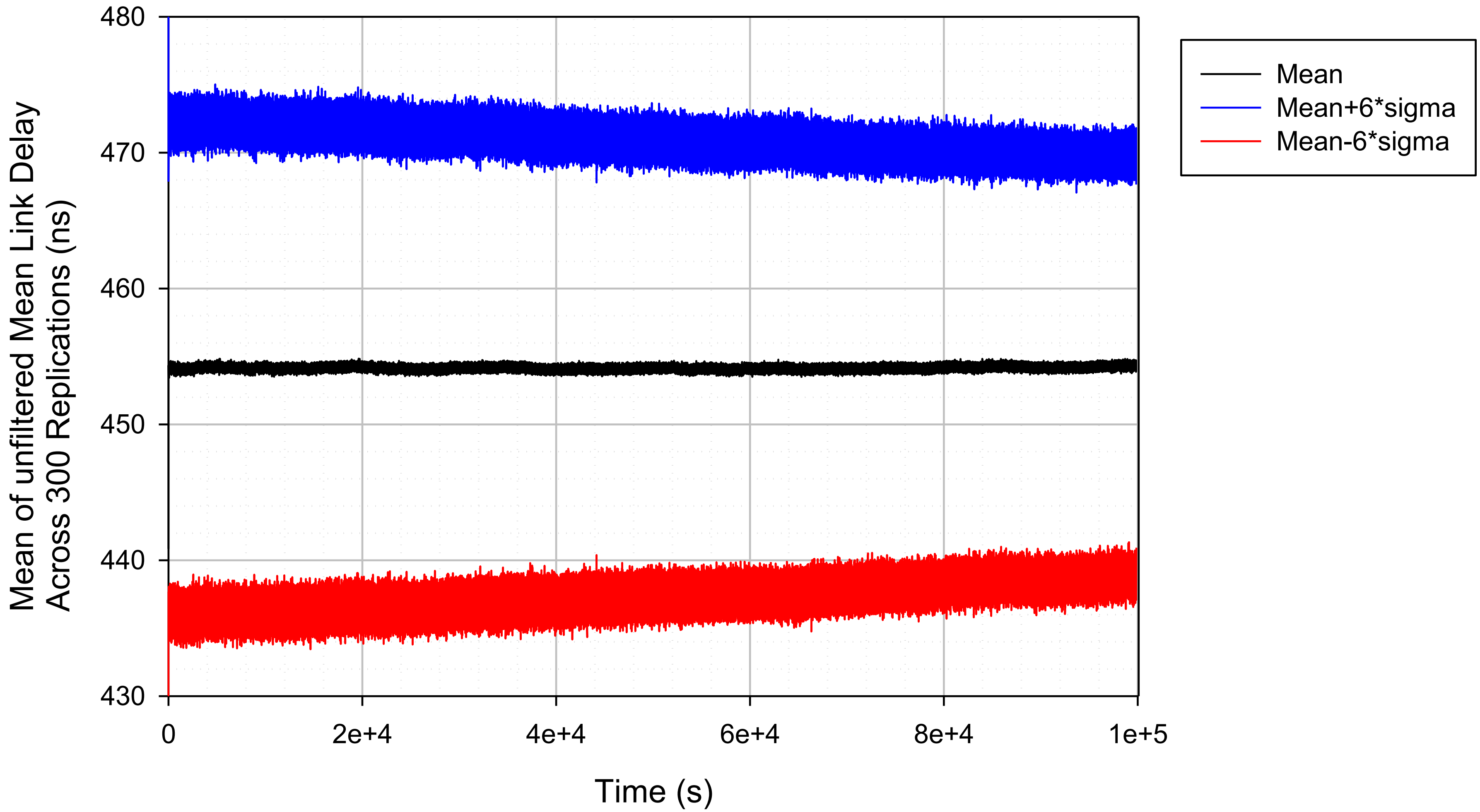



Individual Path Delay Measurements
Experiement 1 - Case 1 - Replication 300
465
460
455
450
445
mPathDelay (ns)
0
2500
5000
7500
10000
12500
Time (s)

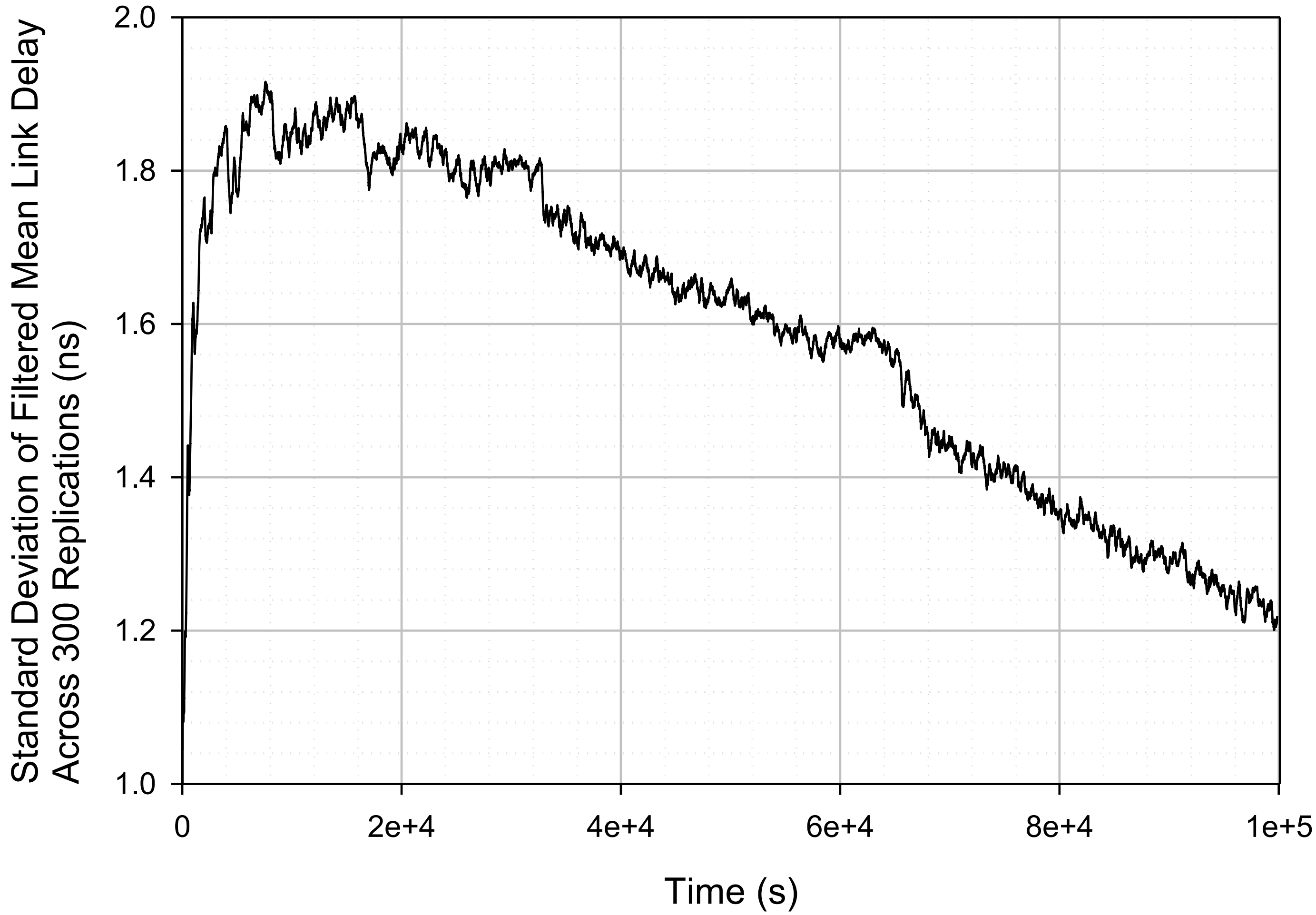
Case01
Mean, mean+6*sigma, mean-6*sigma, of mean link delay after IIR filtering, across 300 replications (Ensemble average)



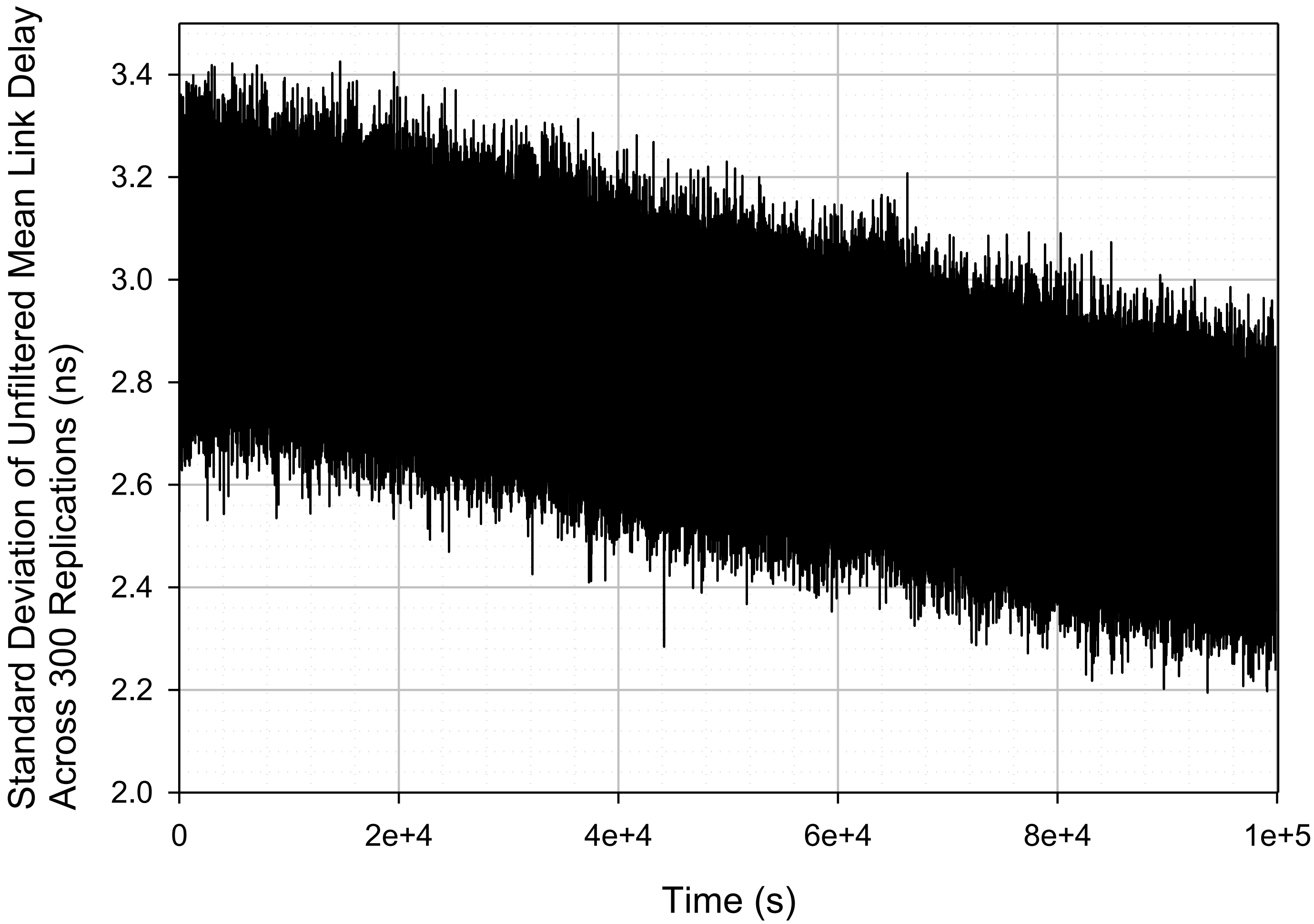
Case01
Mean, mean+6*sigma, mean-6*sigma, of mean link delay before IIR filtering, across 300 replications (Ensemble average)



Case01
Standard deviation of mean link delay after IIR filtering, across 300 replications (Ensemble average)



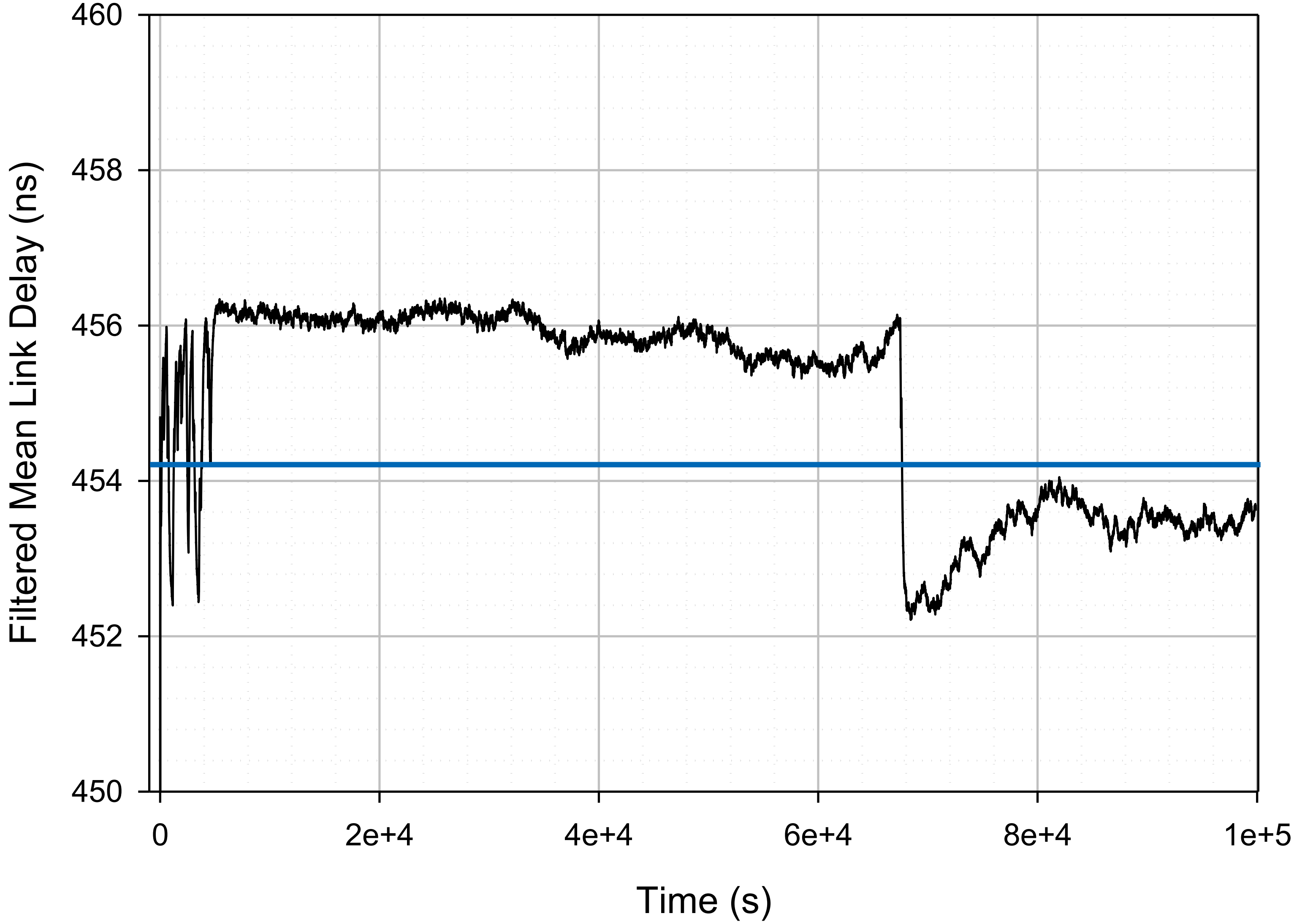
Case01
Standard deviation of mean link delay before IIR filtering, across 300 replications (Ensemble average)



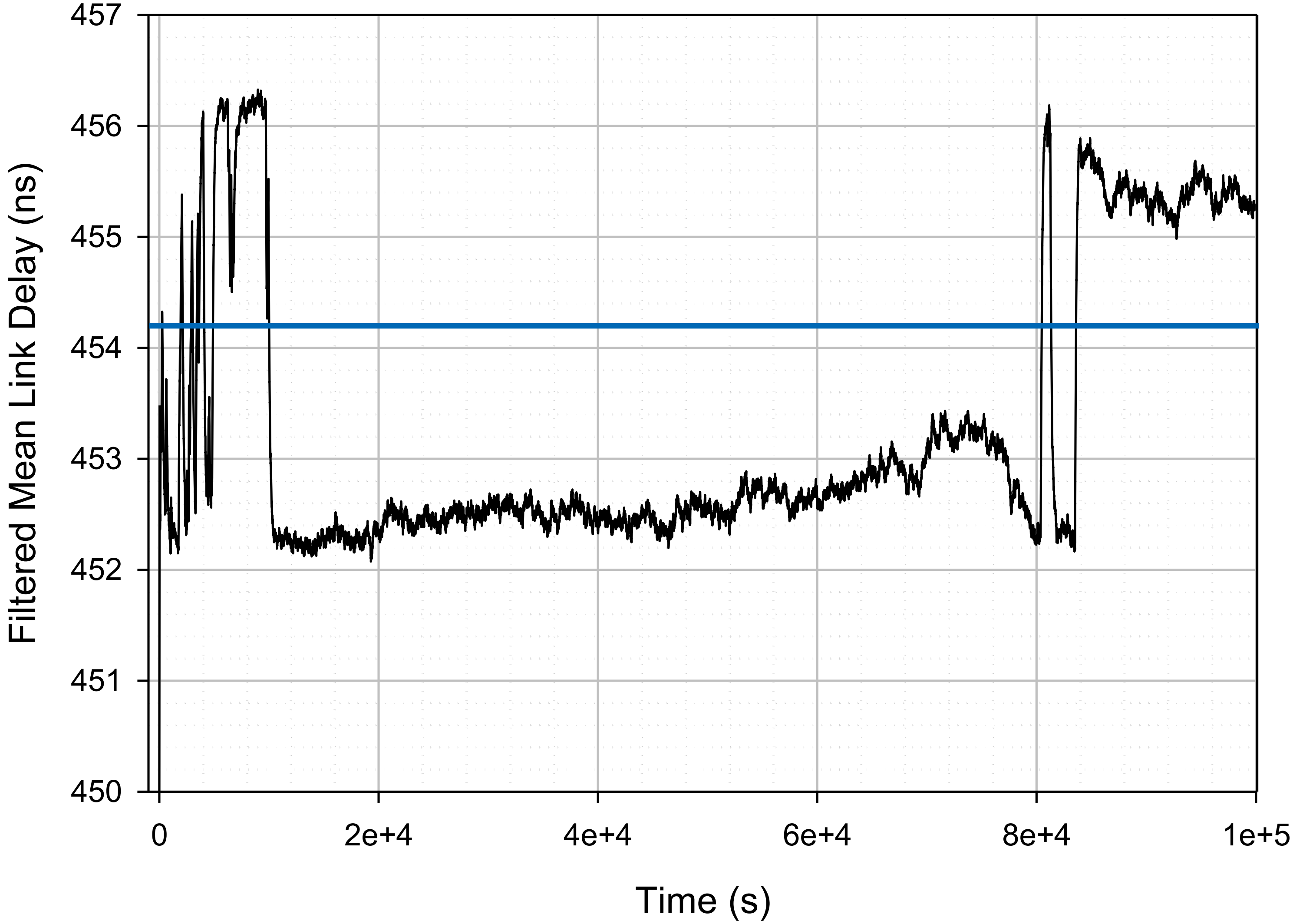
Results for Case 1b – following 10 slides

- The scatter plots on slides 45 and 47, and the average level indications, were supplied by David McCall, March 2024.

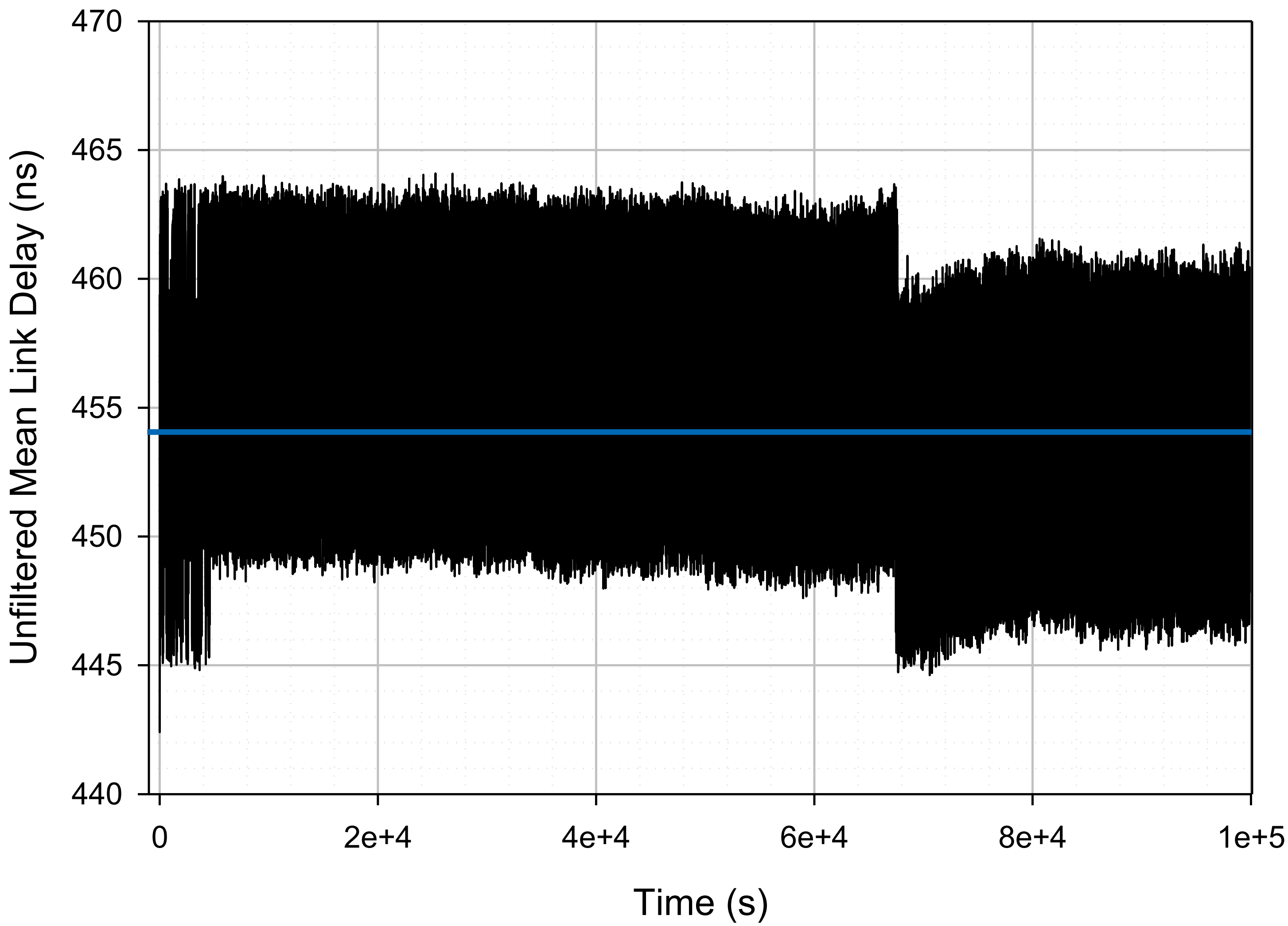
Case01b - Mean Link Delay after IIR Filtering - Replication 1

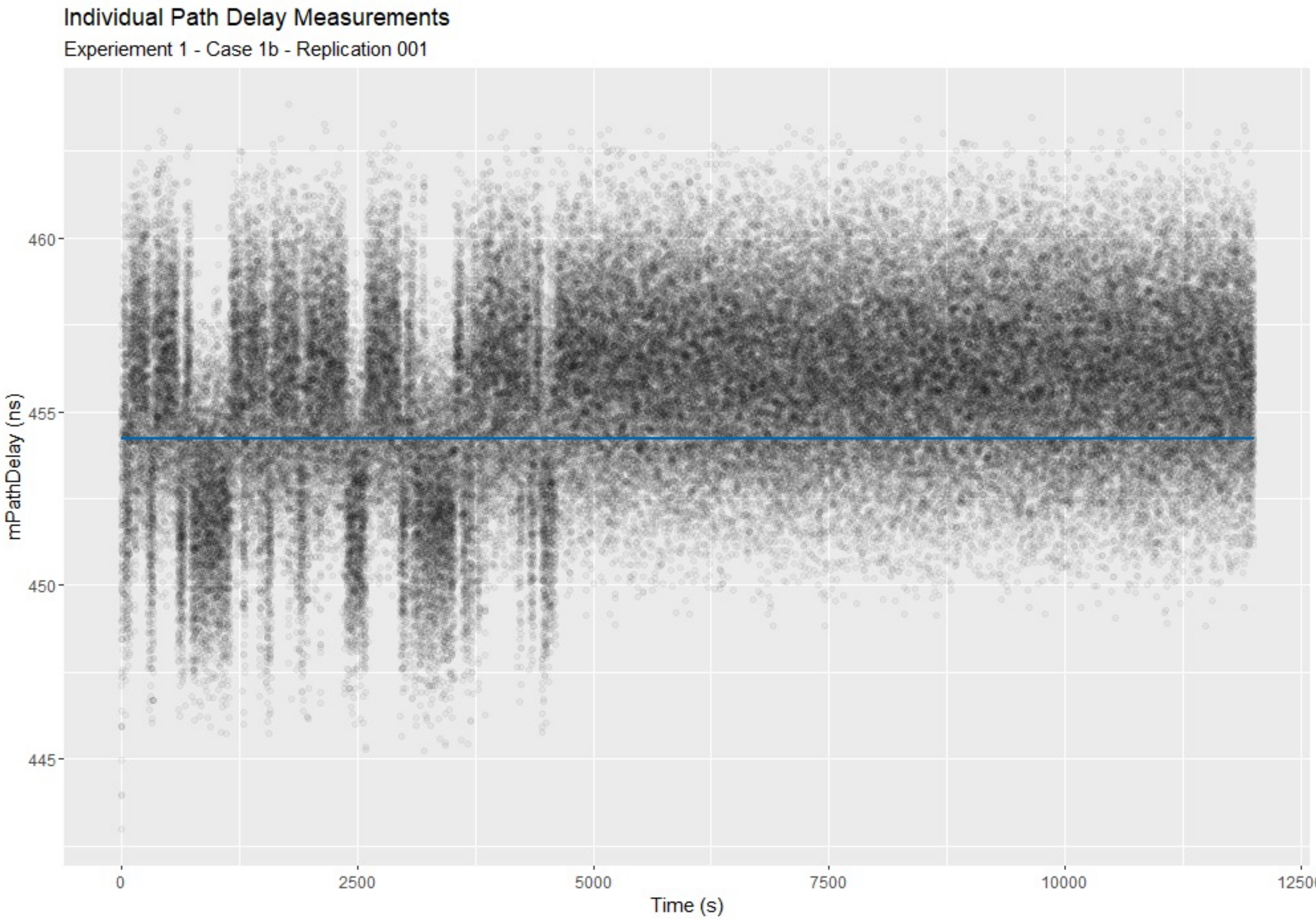


Case01b - Mean Link Delay after IIR Filtering - Replication 300

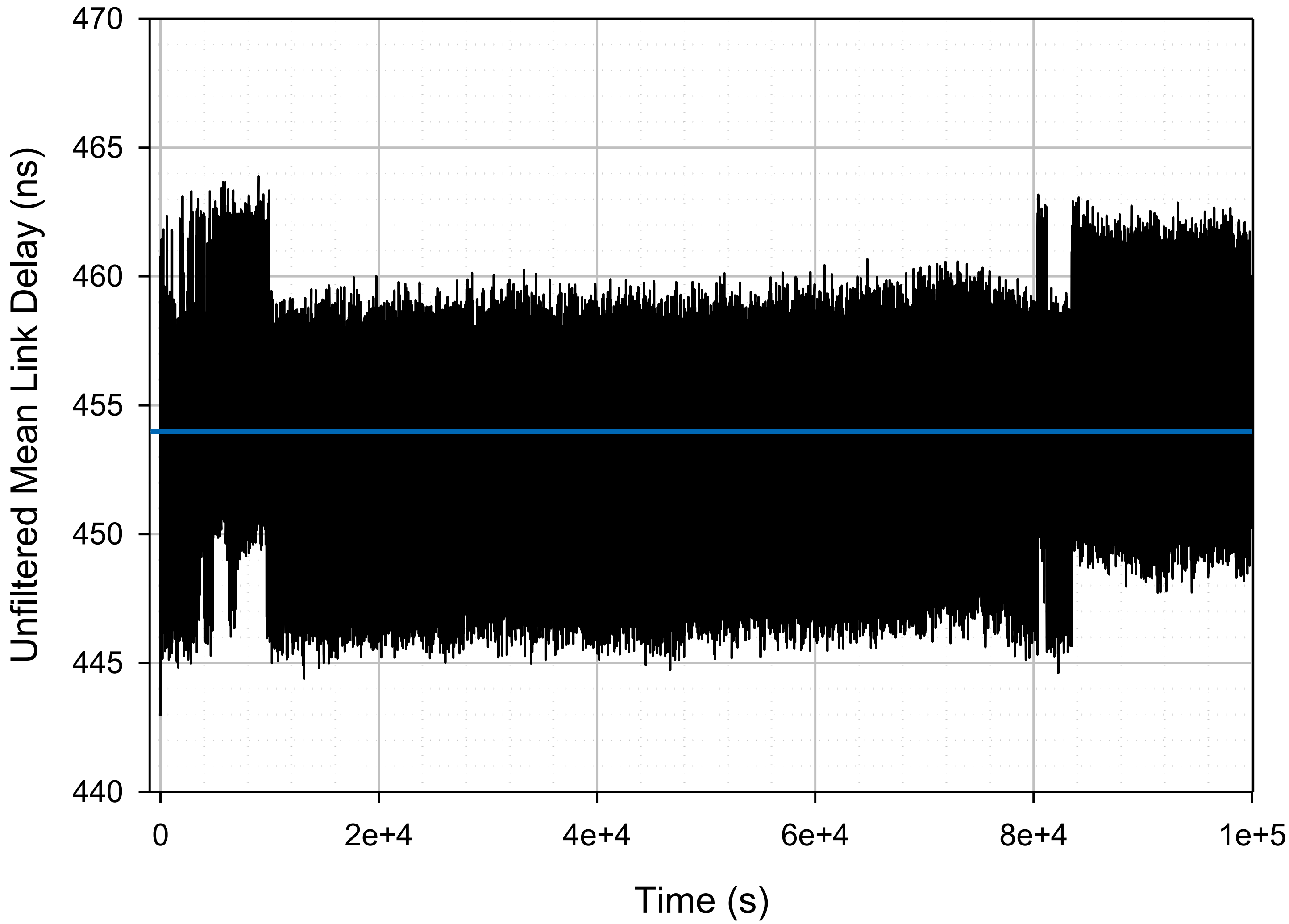


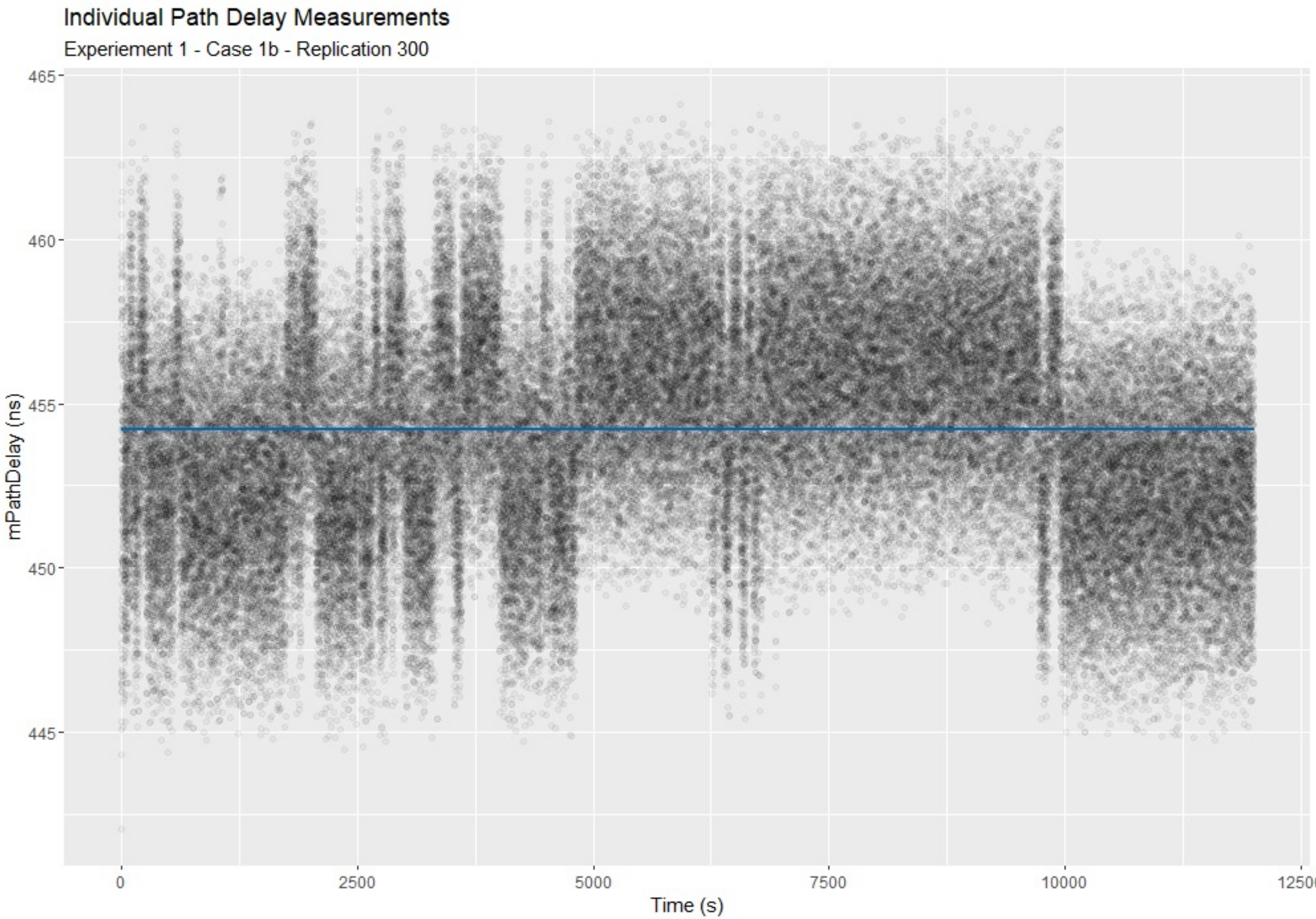
Case01b - Mean Link Delay before IIR Filtering - Replication 1



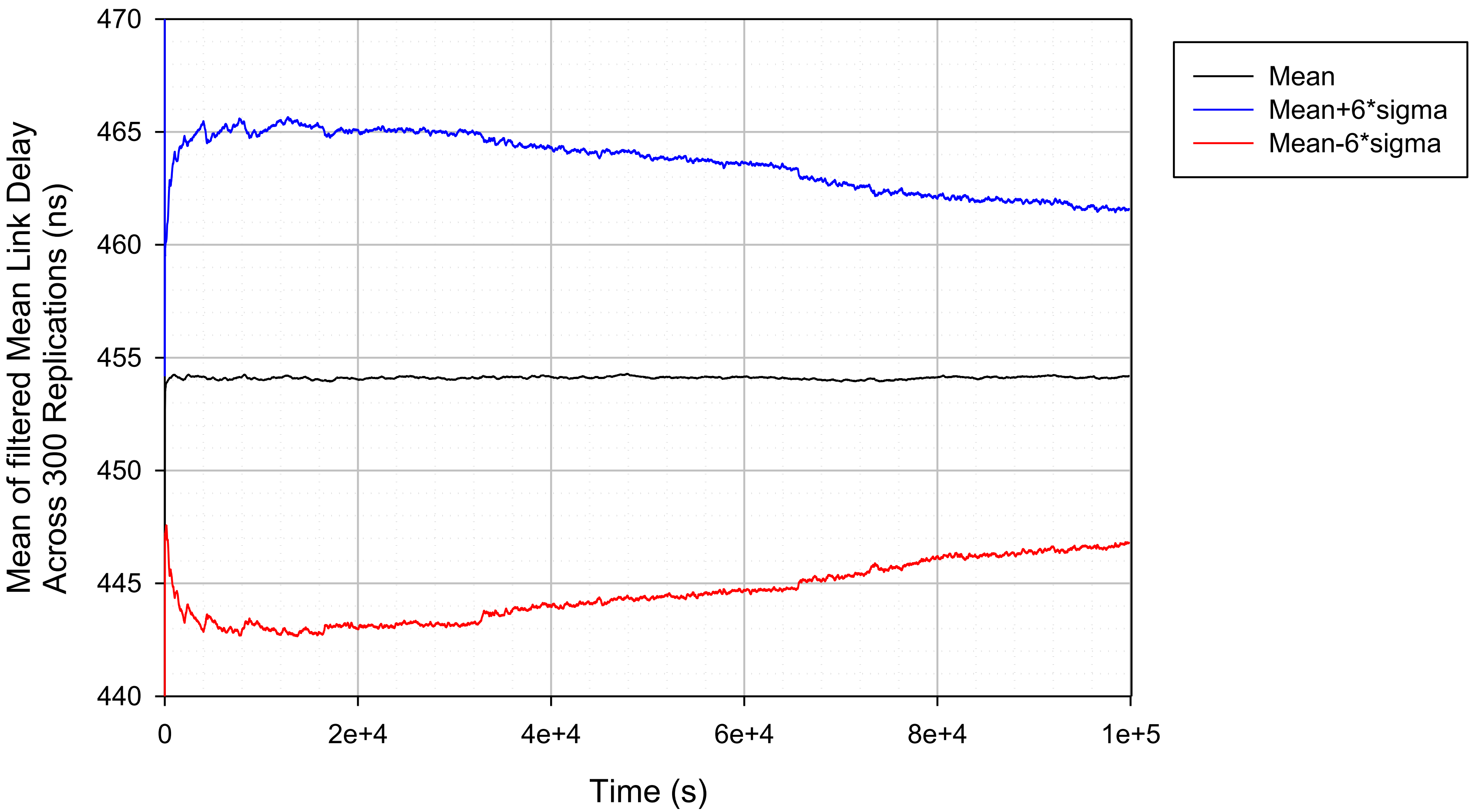

Individual Path Delay Measurements
Experiement 1 - Case 1b - Replication 001
mPathDelay (ns)
460
455
450
445
0
2500
5000
7500
10000
12500
Time (s)

Case01b - Mean Link Delay before IIR Filtering - Replication 300

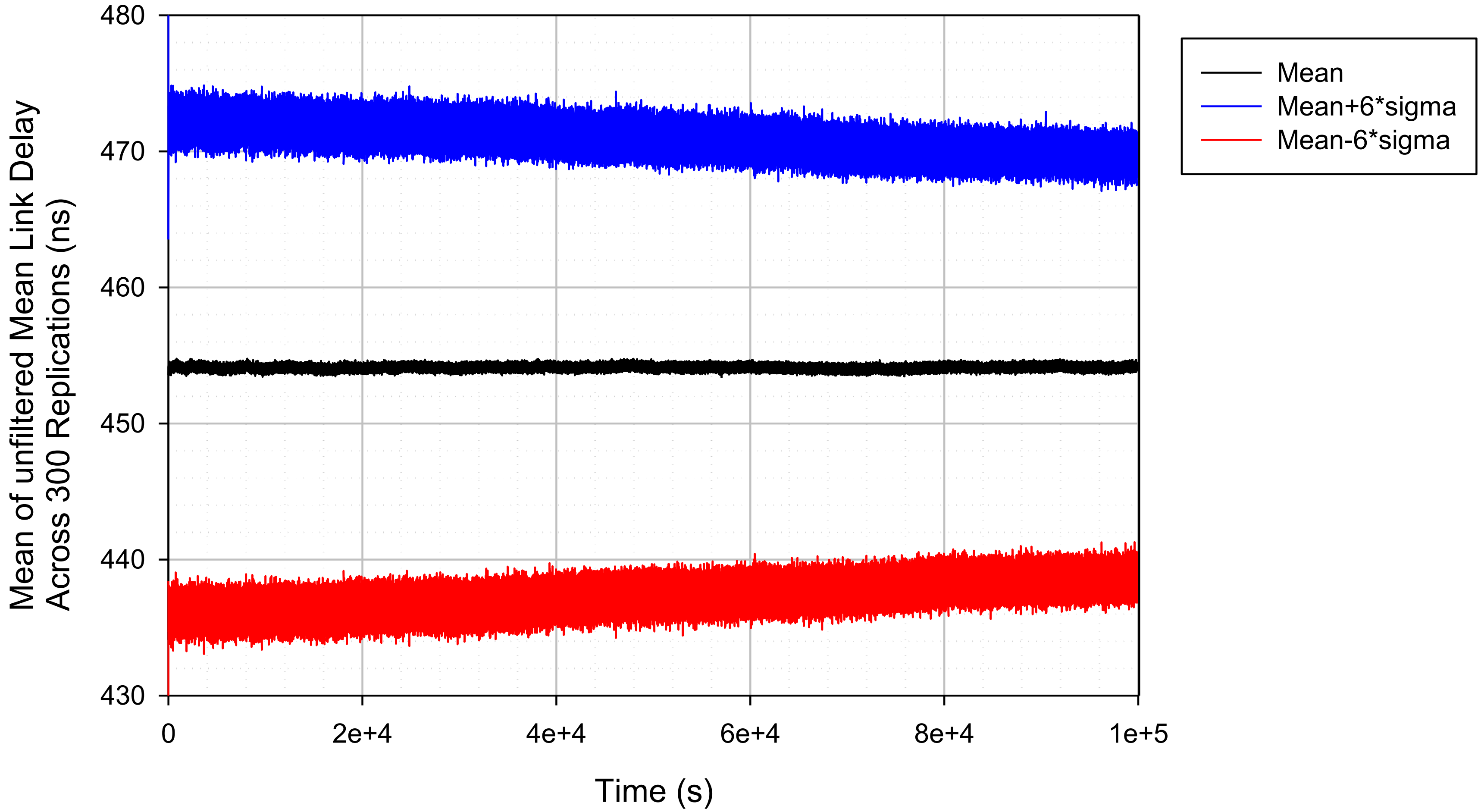



Individual Path Delay Measurements
Experiement 1 - Case 1b - Replication 300
465
460
455
450
445
mPathDelay (ns)
0
2500
5000
7500
10000
12500
Time (s)

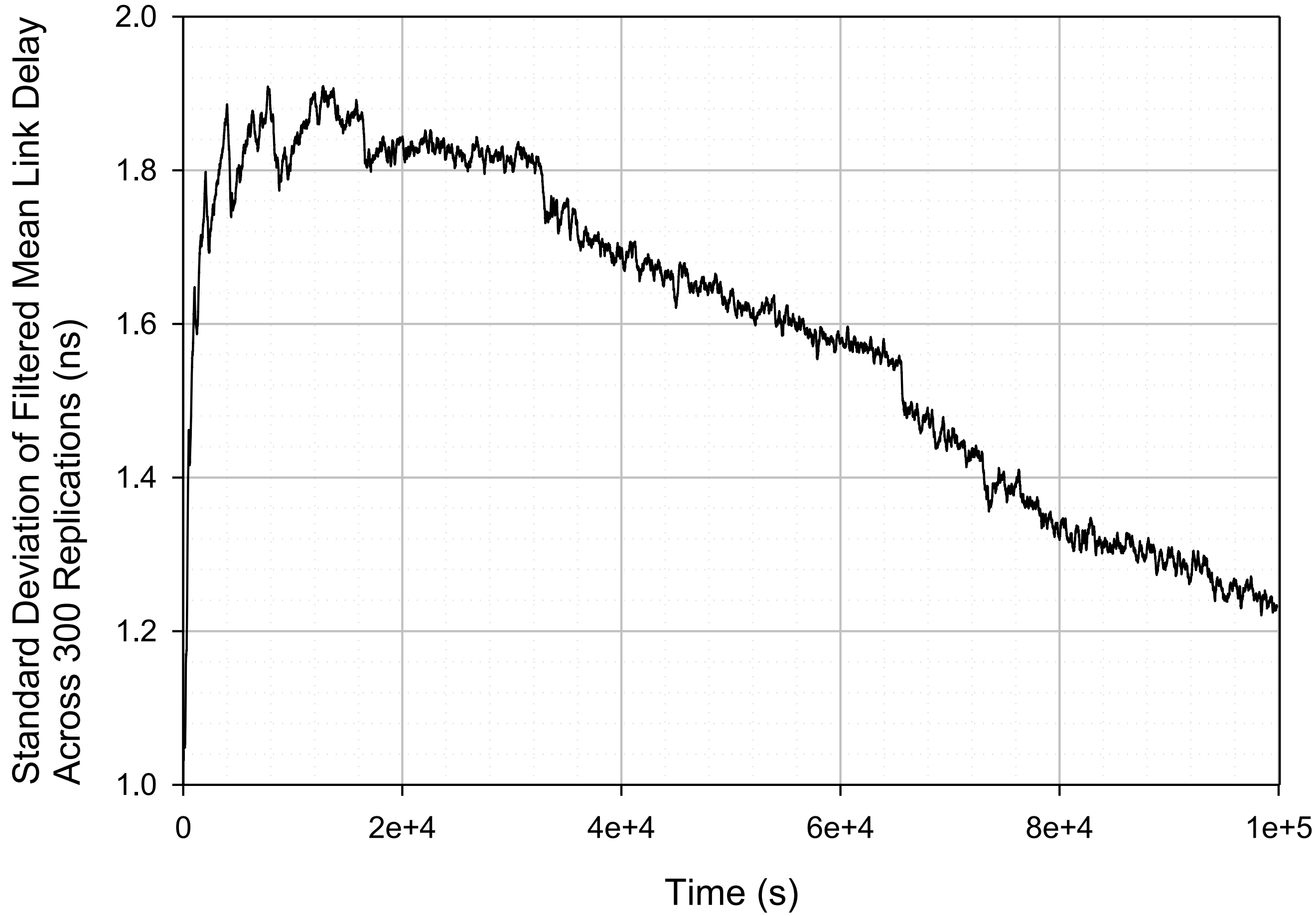
Case01b
Mean, mean+6*sigma, mean-6*sigma, of mean link delay after IIR filtering, across 300 replications (Ensemble average)



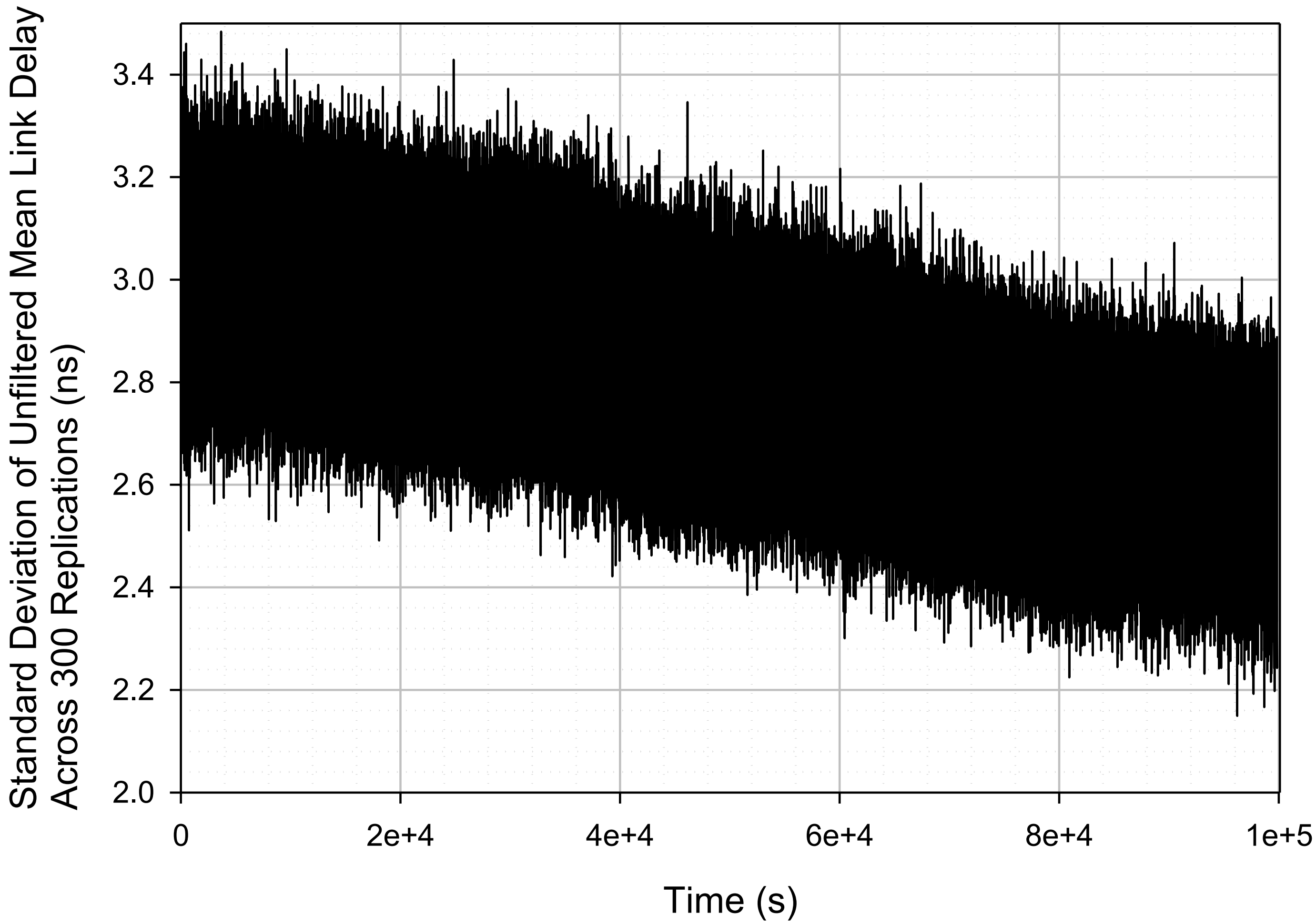
Case01b
Mean, mean+6*sigma, mean-6*sigma, of mean link delay before IIR filtering, across 300 replications (Ensemble average)



Case01b
Standard deviation of mean link delay after IIR filtering, across 300 replications (Ensemble average)



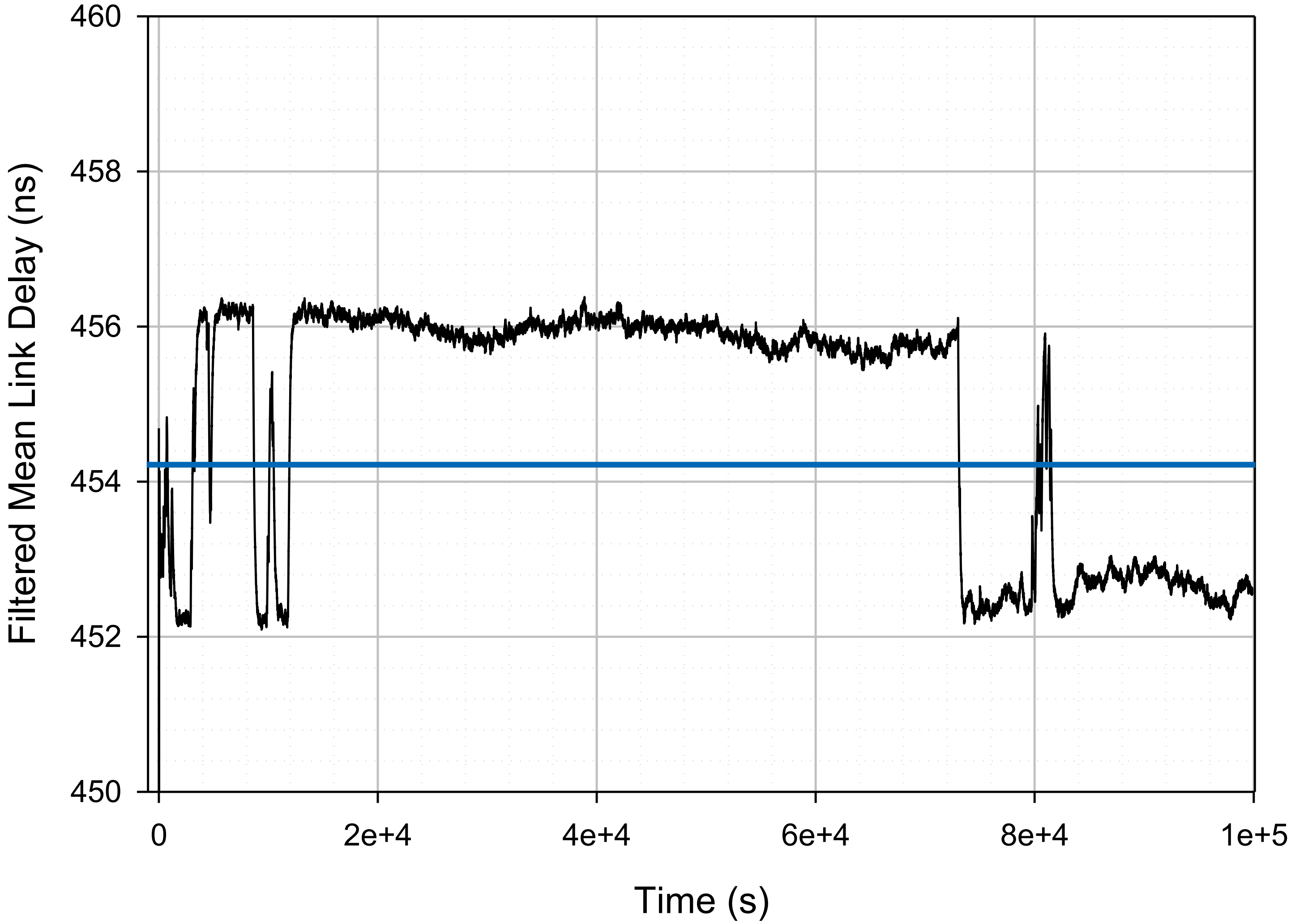
Case01b
Standard deviation of mean link delay before IIR filtering, across 300 replications (Ensemble average)



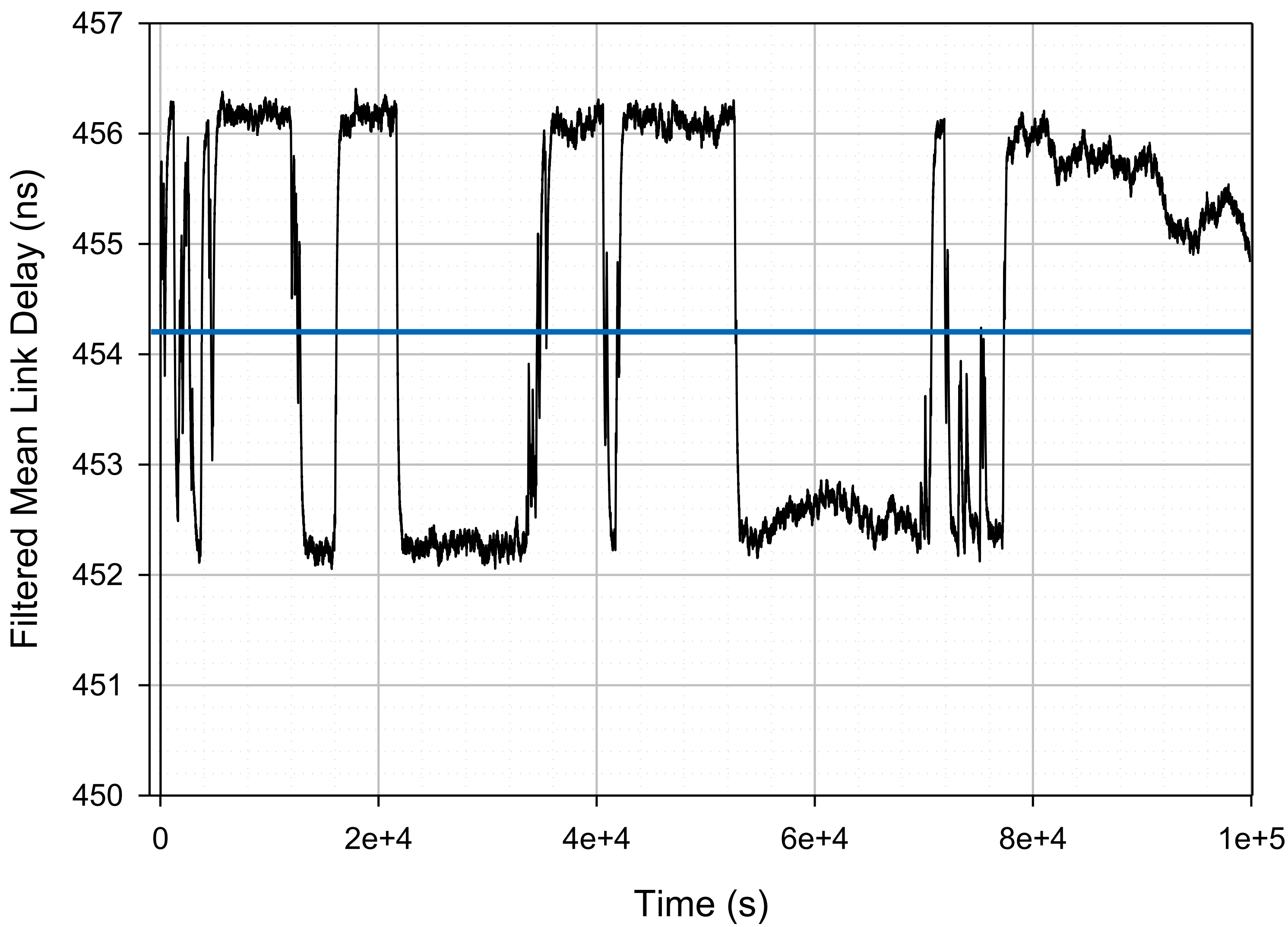
Results for Case 1c - following 10 slides

- The scatter plots on slides 56 and 58, and the average level indications, were supplied by David McCall, March 2024.

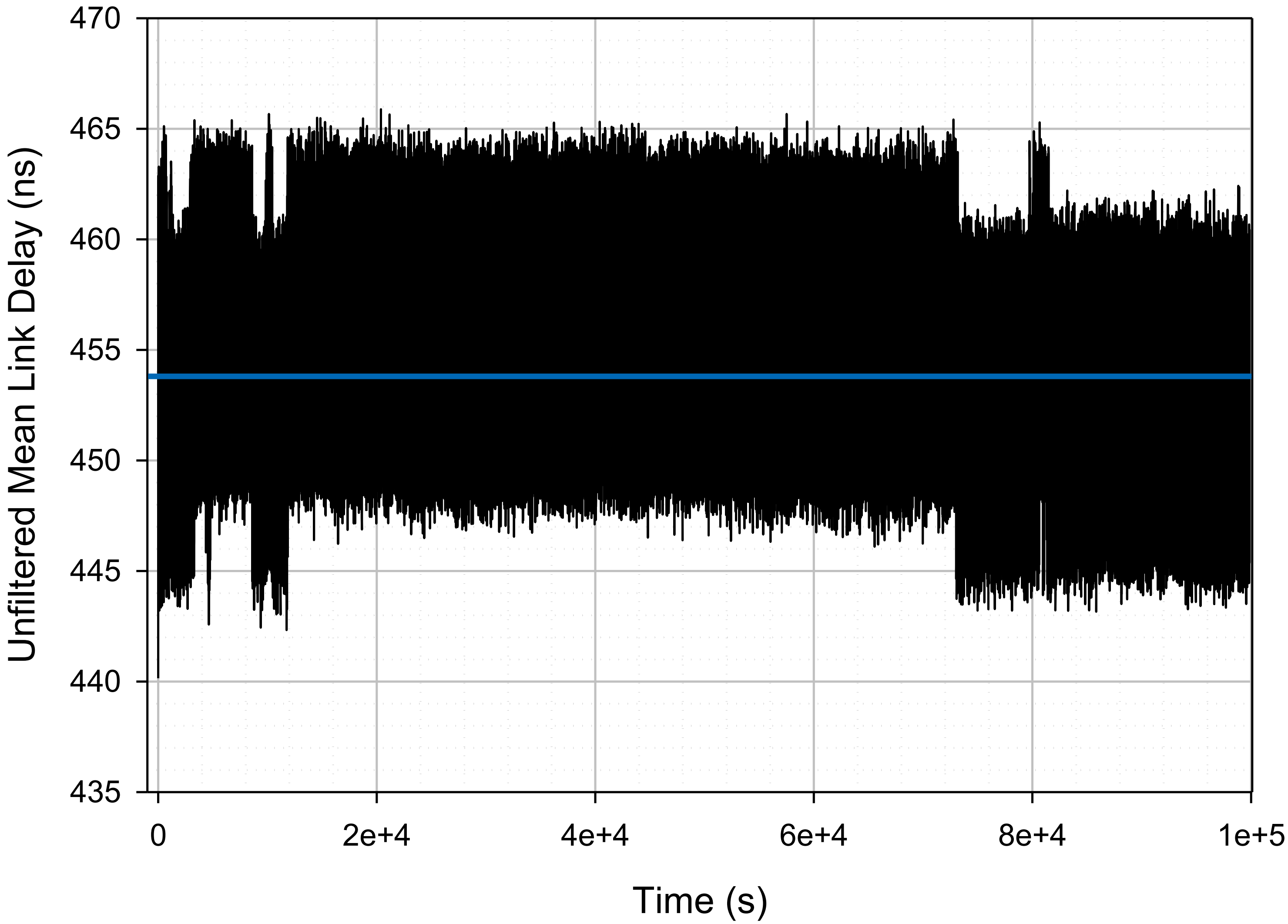
Case01c - Mean Link Delay after IIR Filtering - Replication 1

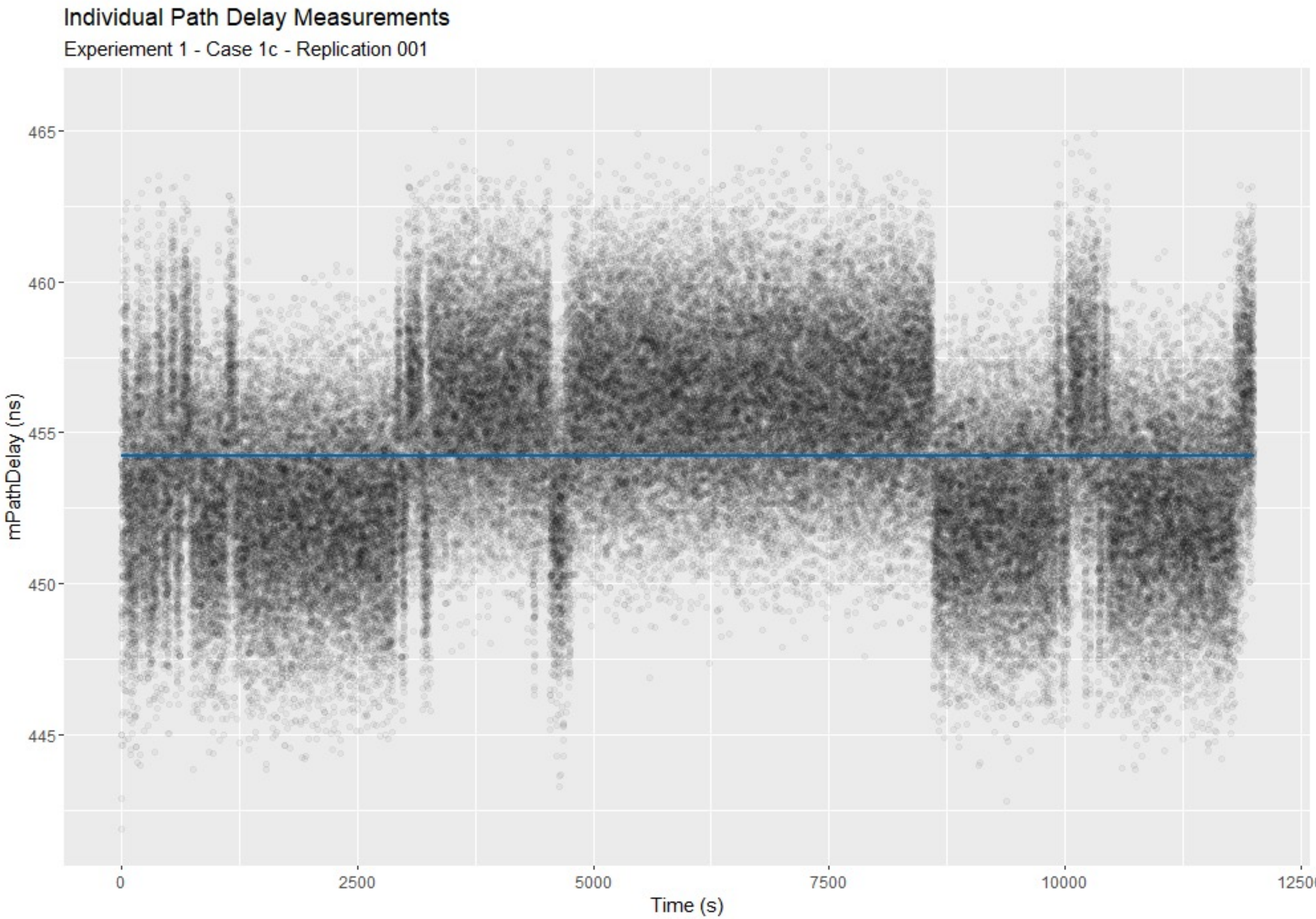


Case01c - Mean Link Delay after IIR Filtering - Replication 300

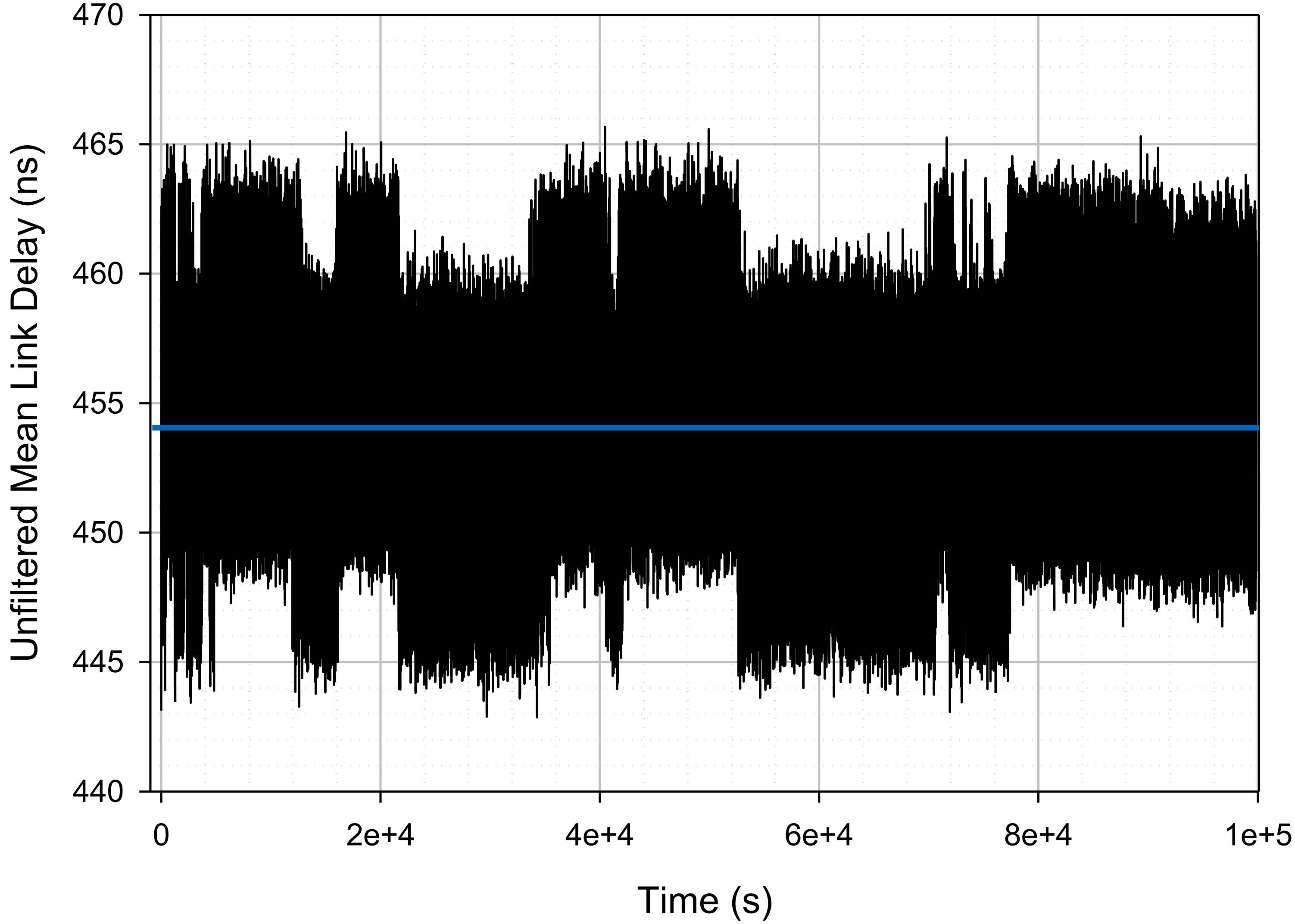


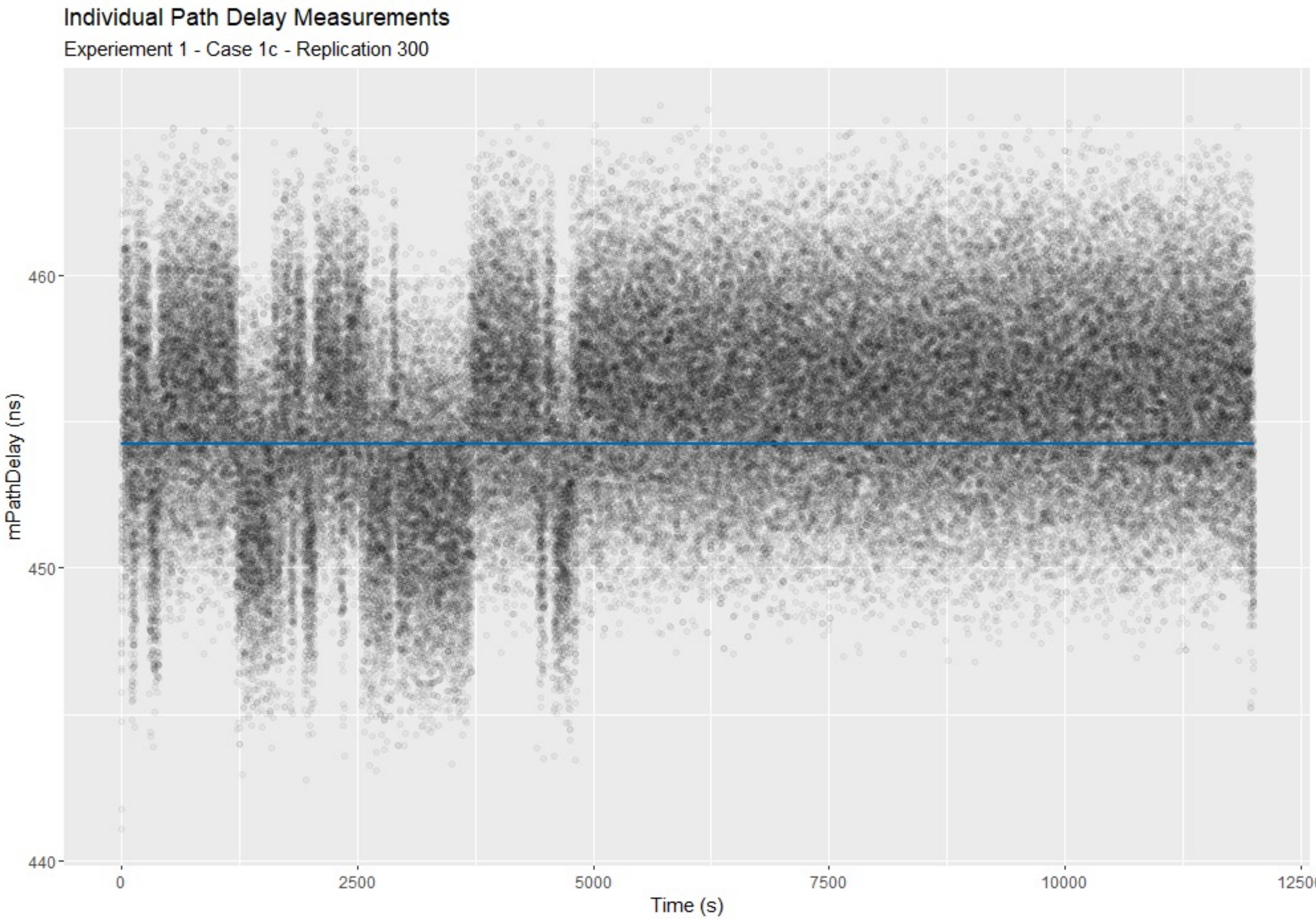
Case01c - Mean Link Delay before IIR Filtering - Replication 1




Individual Path Delay Measurements
Experiement 1 - Case 1c - Replication 001
465
460
455
450
445
mPathDelay (ns)
0
2500
5000
7500
10000
12500
Time (s)

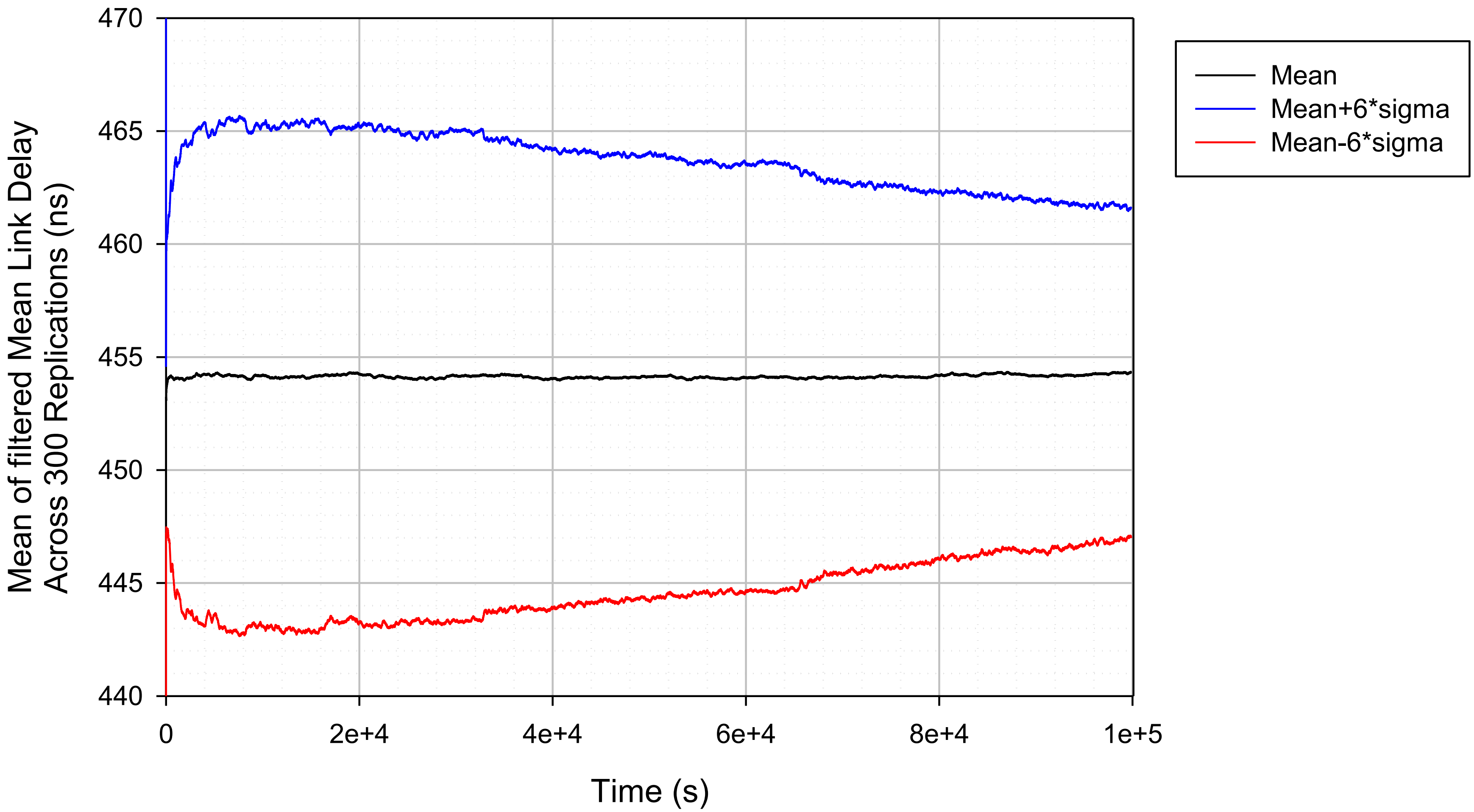
Case01c - Mean Link Delay before IIR Filtering - Replication 300



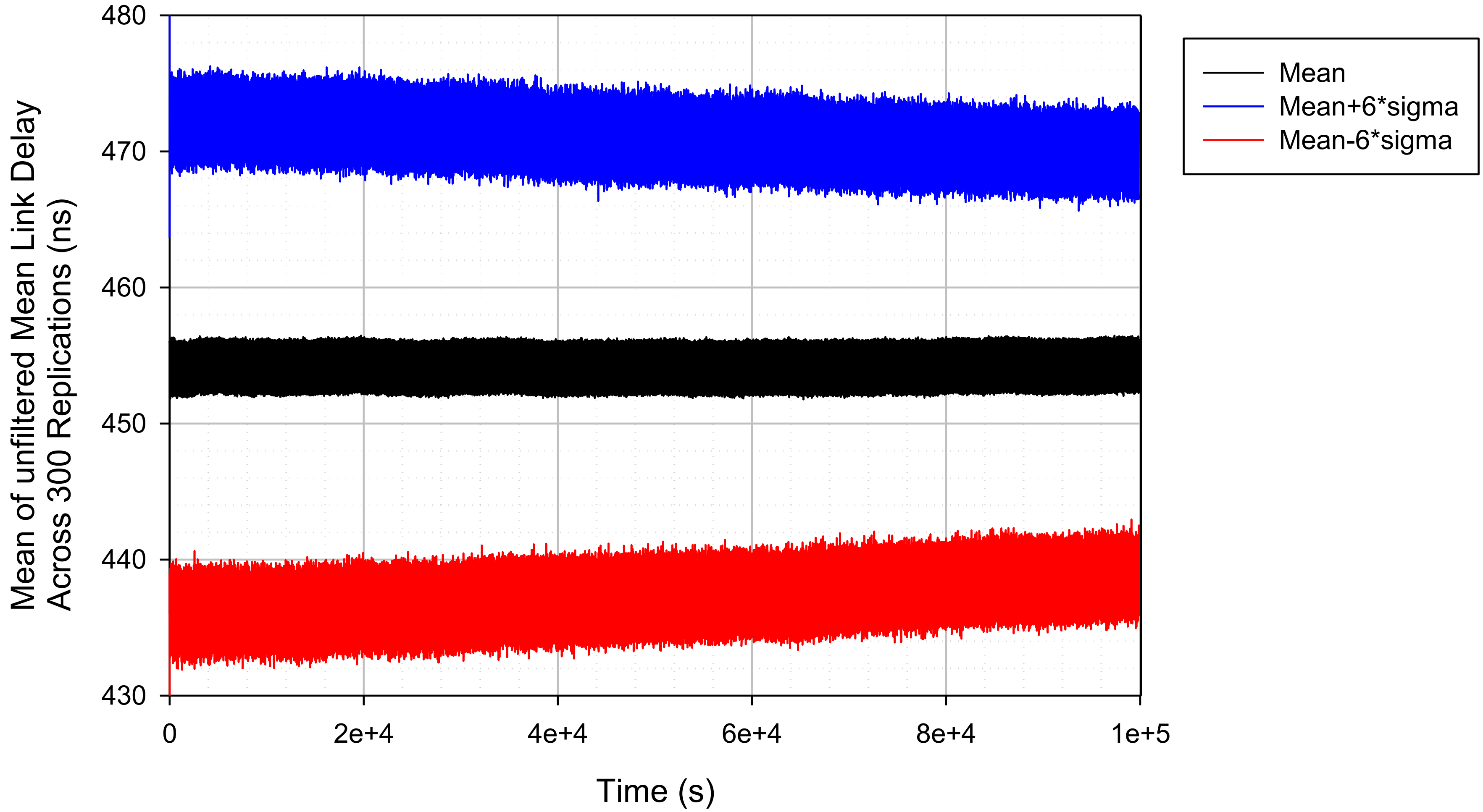


Individual Path Delay Measurements
Experiement 1 - Case 1c - Replication 300
460
450
440
mPathDelay (ns)
0
2500
5000
7500
10000
12500
Time (s)

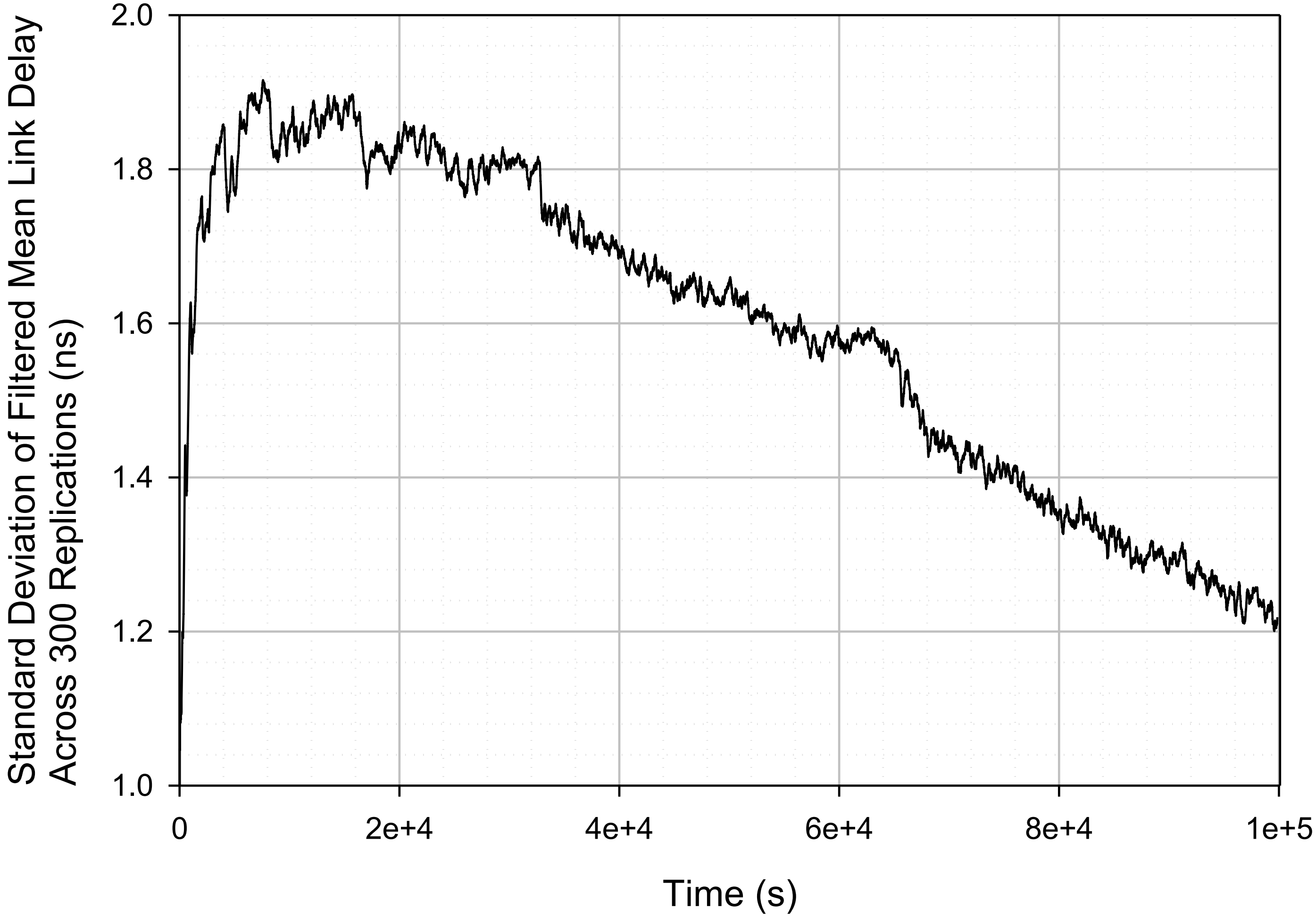
Case01c
Mean, mean+6*sigma, mean-6*sigma, of mean link delay after IIR filtering, across 300 replications (Ensemble average)



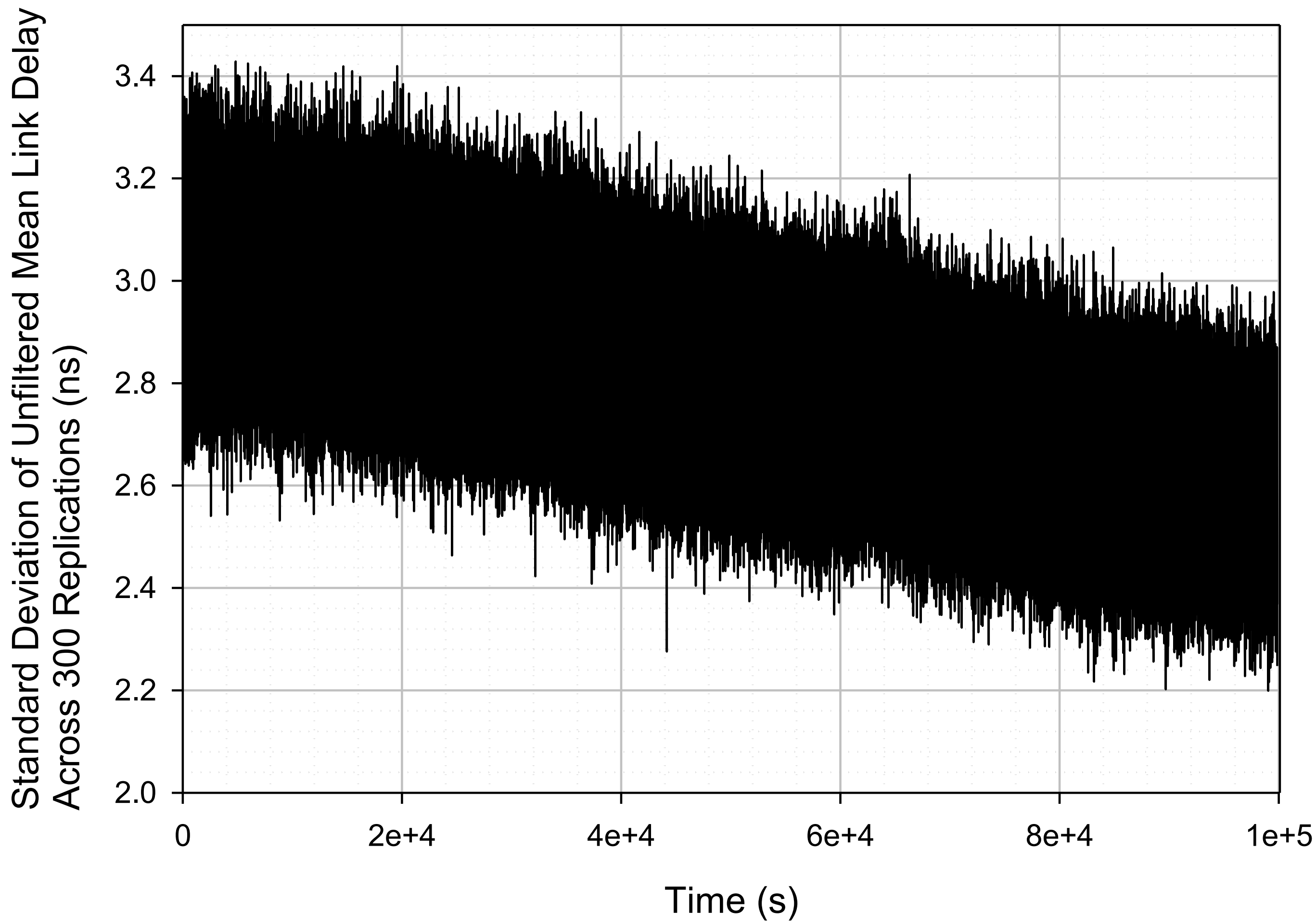
Case01c
Mean, mean+6*sigma, mean-6*sigma, of mean link delay before IIR filtering, across 300 replications (Ensemble average)



Case01c
Standard deviation of mean link delay after IIR filtering, across 300 replications (Ensemble average)

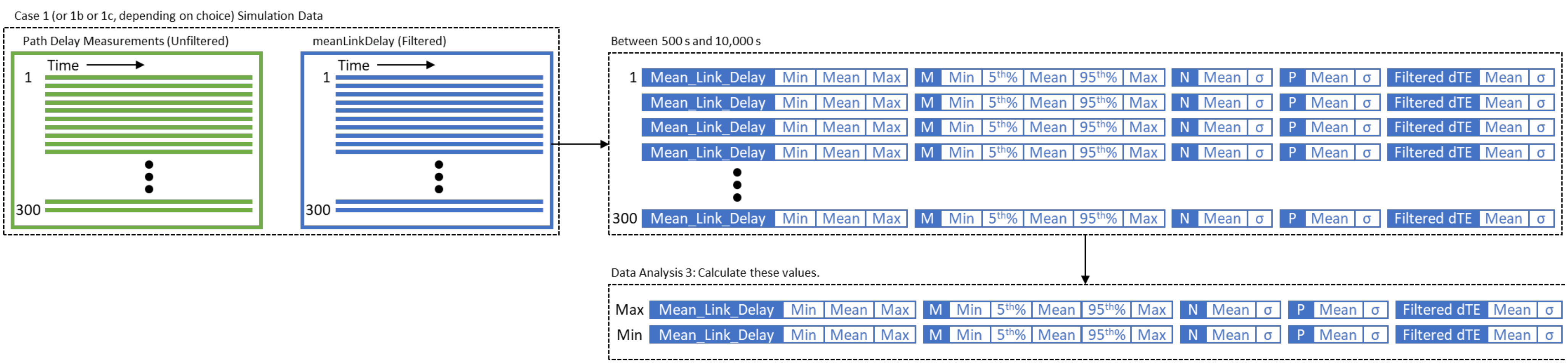


Case01c
Standard deviation of mean link delay before IIR filtering, across 300 replications (Ensemble average)



Experiment 1, Data Analysis 3 - 1

- Data analysis 3, as described in [9], with some additional results
- For each of the 300 replications, calculate the following statistics over time for filtered mean link delay, M, N, P, and filtered dTE:
  - Minimum, 5th percentile, 95th percentile, maximum, mean, standard deviation
  - For each of the above statistics, compute the minimum and maximum value over the 300 replications (see figure below, which is taken from[10])



Experiment 1, Data Analysis 3 - 2

- The following plots are generated for Replication 1, for each of cases 1, 1b, and 1c (4 plots for each case)
  - M: preciseOriginTimestamp + correctionField – (Working Clock at GM), at node 3, when Sync is sent by node 3
  - N: rateRatio field of Sync message minus actual rateRatio, at node 3, when Sync is sent by node 3
  - P: rateRatioDrift field of Drift_Tracking TLV minus actual rate ratio drift, at node 3, when Sync is sent by node 3
  - Filtered dTE at node 3
- Following the plots, tables of numerical results are provided for minimum and maximum over 300 replications for the above statistics over time of mean link delay after filtering, M, N, P, and filtered dTE

Experiment 1, Data Analysis 3 - 3

- The actual mean link delay for the link between nodes 2 and 3 is 454.21 ns
- The requirement for the mean link delay error in Tables 13 and 14 of [1] is $\pm$3 ns
- This means that the measured mean link delay, after filtering, must be in the range [451.21, 457.21] ns
- All the mean link delay results in the table on slide 83 are within this range
  - For case 1, the minimum is 451.946 ns and the maximum is 456.198 ns
  - For case 1b, the minimum is 451.973 ns and the maximum is 456.191 ns
  - For case 1c, the minimum is 451.935 ns and the maximum is 456.198 ns
  - The ranges for cases 1, 1b, and 1c are almost the same
- The mean link delay error meets the requirement

Experiment 1, Data Analysis 3 - 4

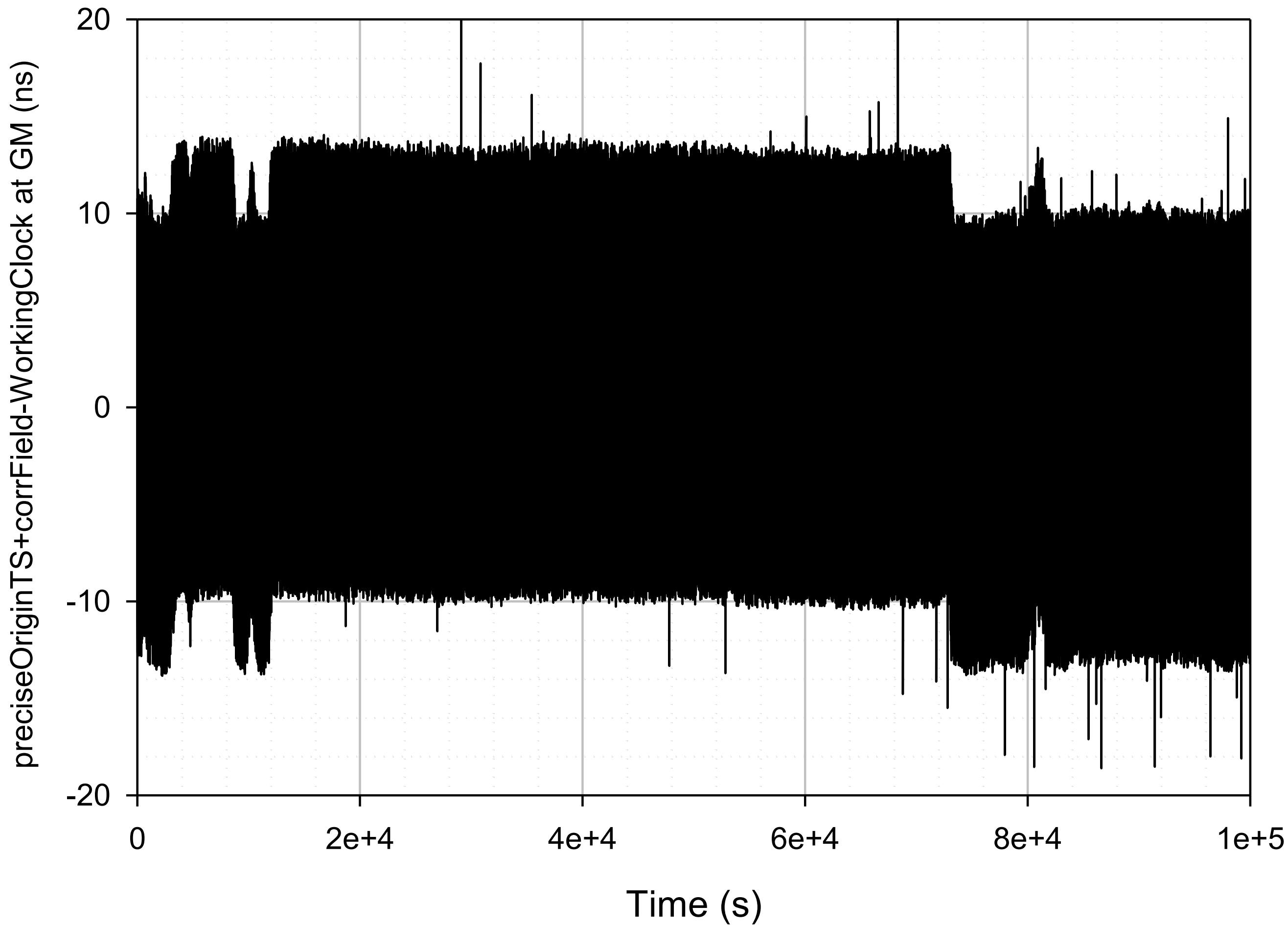
- For M, N, P, and filtered dTE, the requirements of Tables 13 and 14 of [1] are shown in red in the results tables on slides 84 and 85 (for M), 86 (for N), 87 (for P), and 88 (for filtered dTE)
- The requirements are only shown for applicable quantities of Tables 13 and 14, even though other quantities also meet the requirements
  - Therefore, requirements are not shown for cases 1b and 1c because Tables 13 and 14 do not specify tests where clock drift varies as in these cases
  - Also, requirements are not shown for other quantities not specified in Tables 13 and 14 (e.g., mean and standard deviation of M, minimum and maximum values of various percentiles of N and P, standard deviation of filtered dTE

Experiment 1, Data Analysis 3 - 5

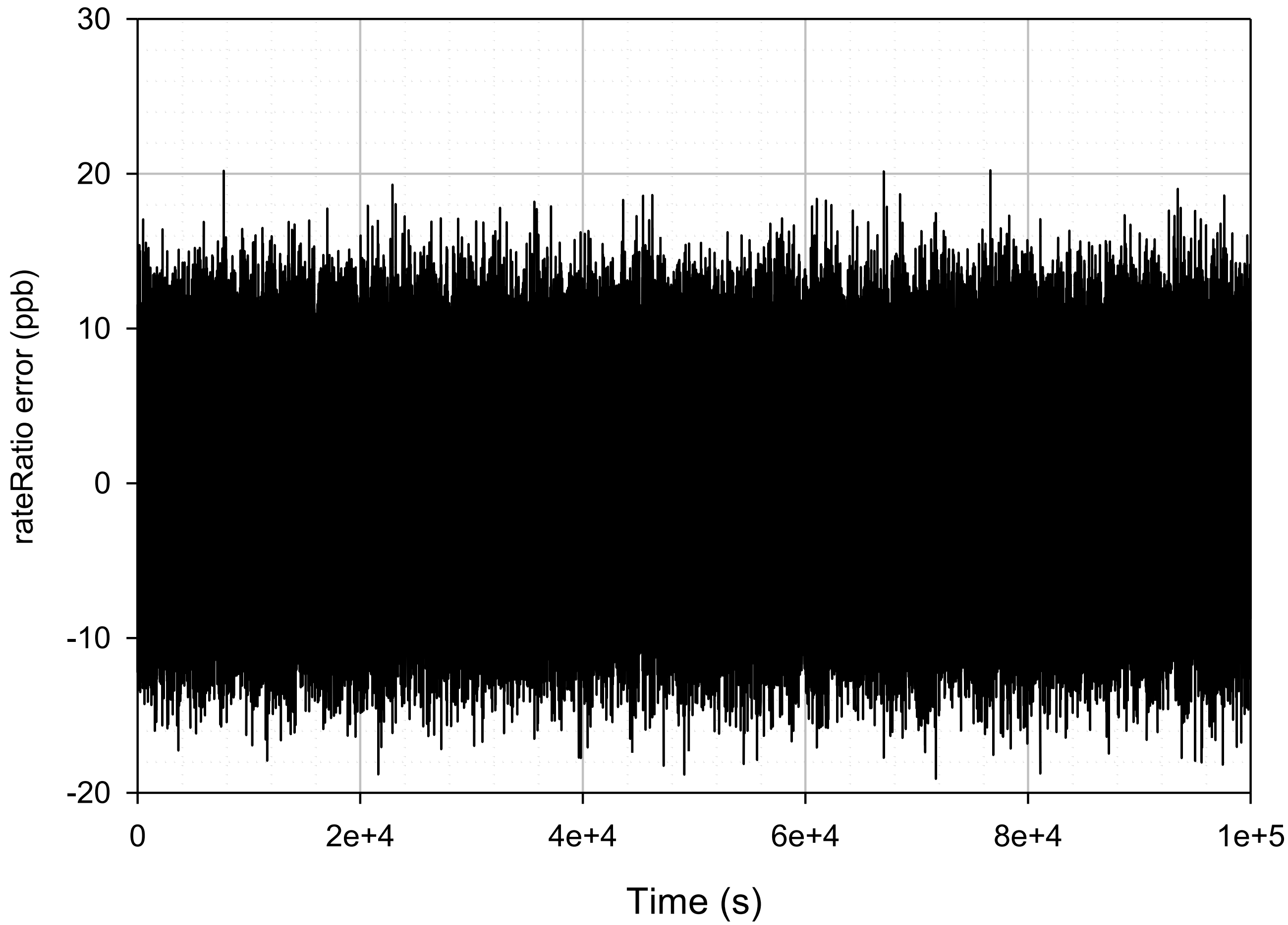
- All of the relevant quantities meet the requirements of Tables 13 and 14
  - The Table 13 requirements on M indicate that the range around the measured mean within which 90% of the measurements fall must be ±10 ns, and the range within which 100% of the measurements fall must be ±20 ns
  - The measured mean ranges from -1.973 ns to 2.008 ns, and is in general different on each replication
  - Therefore, the range of M minus the measured mean (over time) for the respective replication should be compared with the respective requirement
  - The 5th and 95^{th} percentile values for M minus the measured mean, over 300 replications, should be compared with the range for 90% of the measurements, i.e., ±10 ns
  - The minimum and maximum values for M minus the measured mean, over 300 replications, should be compared with the range for 100% of the measurements, i.e., ±20 ns
  - The results, in the table on slide 85, all meet the respective requirements

Plots for Case 1 – following 4 slides

Case 1, Replication 1
preciseOriginTimestamp + correctionField - Working Clock at GM at transmission of Sync message
Node 3



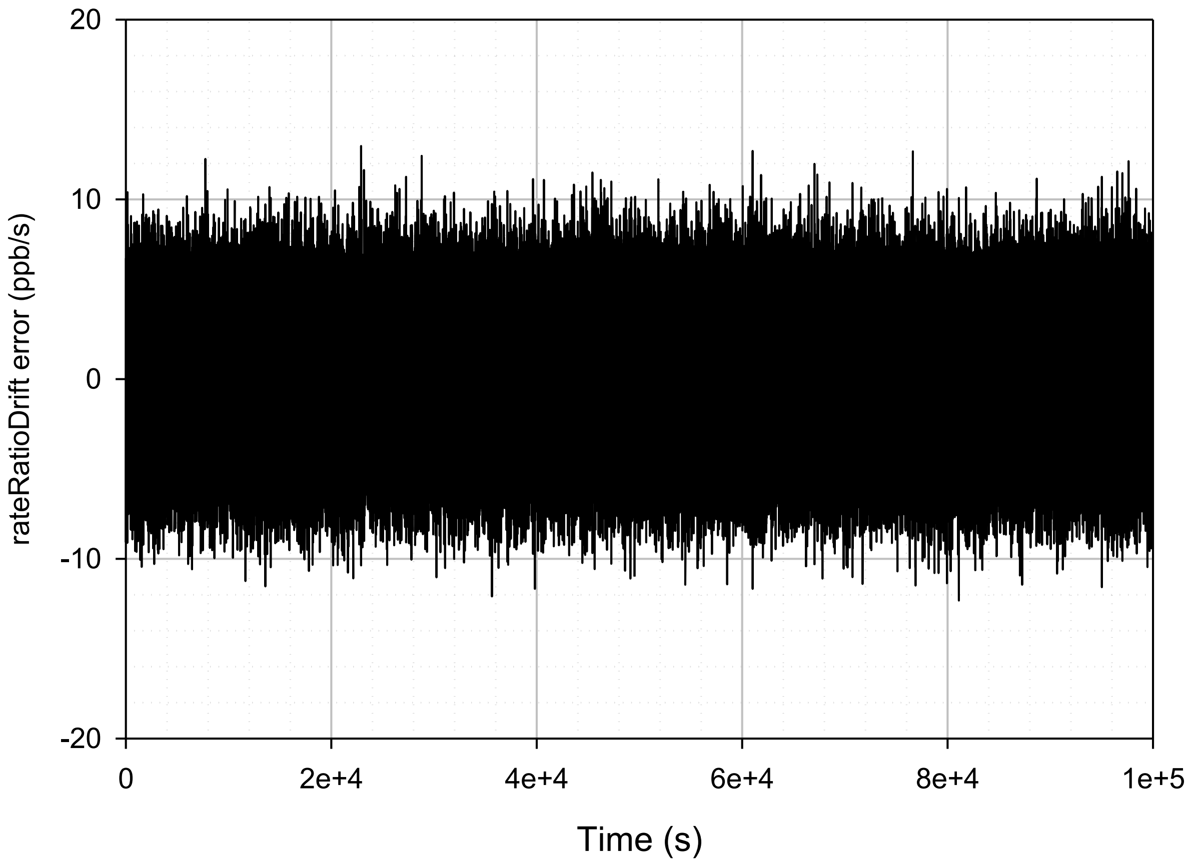
Case 1, Replication 1
rateRatio field of transmitted Sync message by DUT minus actual rate ratio of DUT working clock relative to Working Clock at GM at transmission of Sync message
Node 3



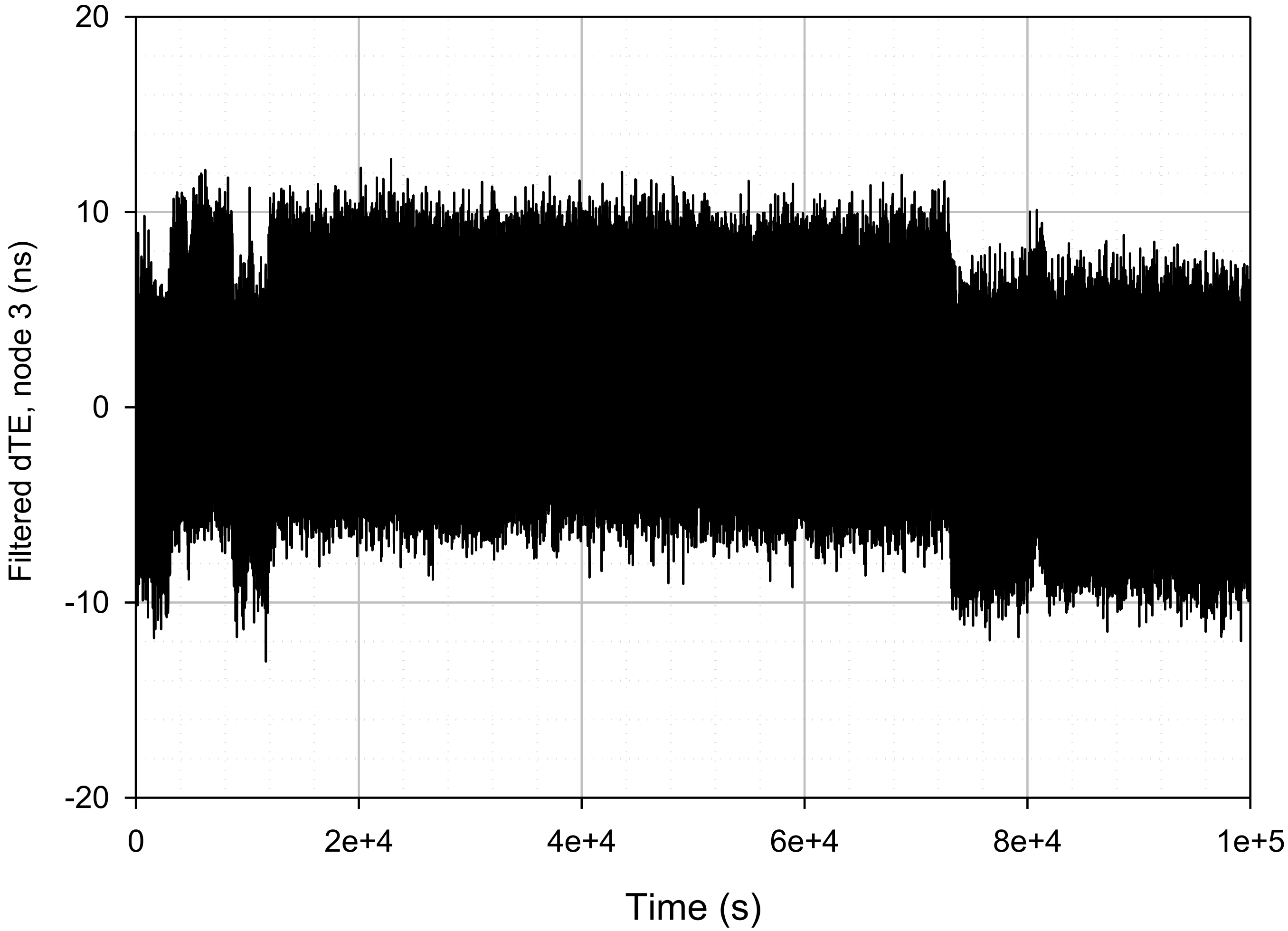
Case 1, Replication 1

rateRatioDrift field of transmitted Sync message by DUT minus actual rate ratio drift rate of DUT working clock relative to Working Clock at GM at transmission of Sync message

Node 3

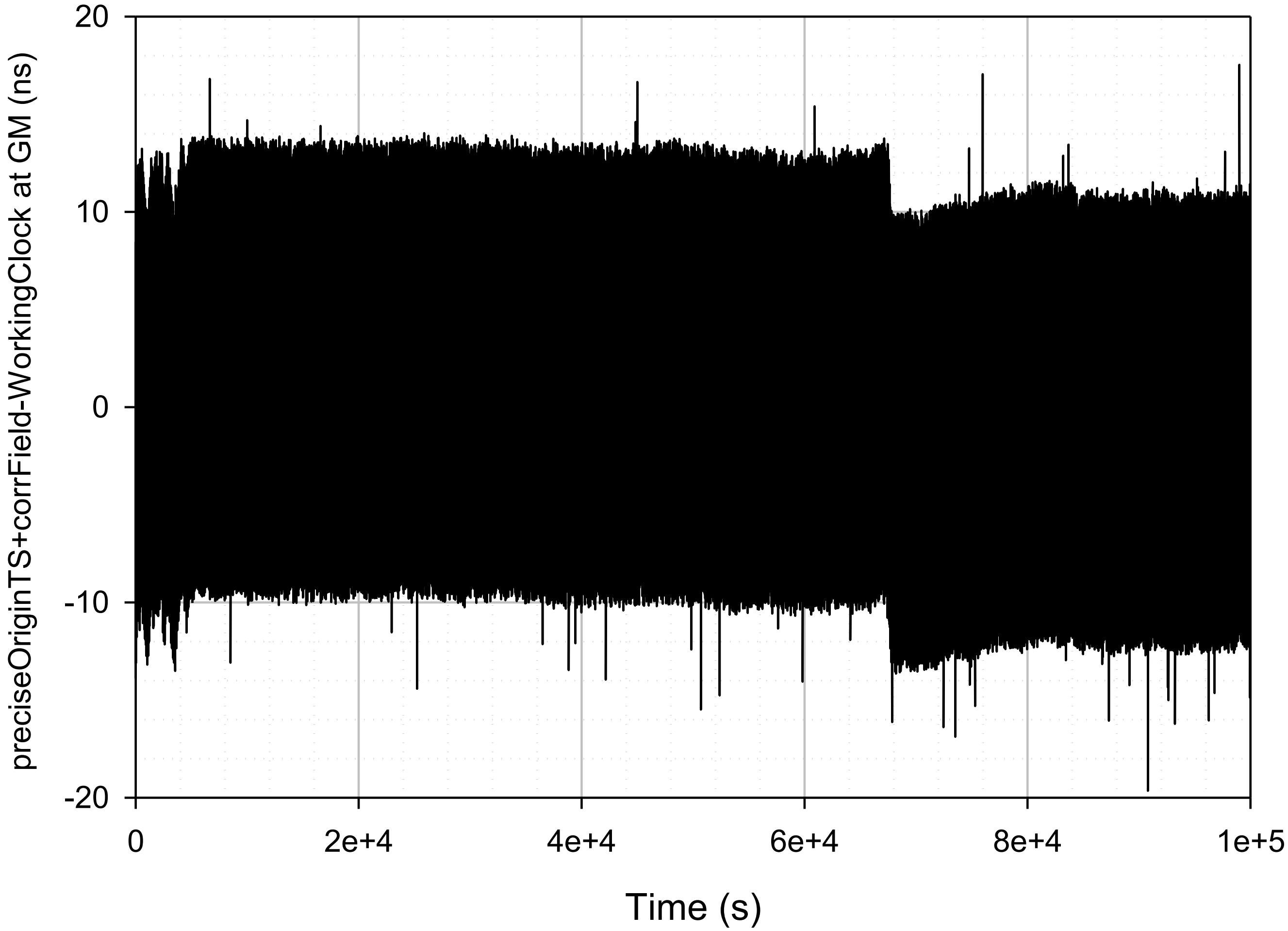


Case 1, Replication 1
Filtered dTE (PTP End Instance), Node 3
Detail of 2 - 100000 s

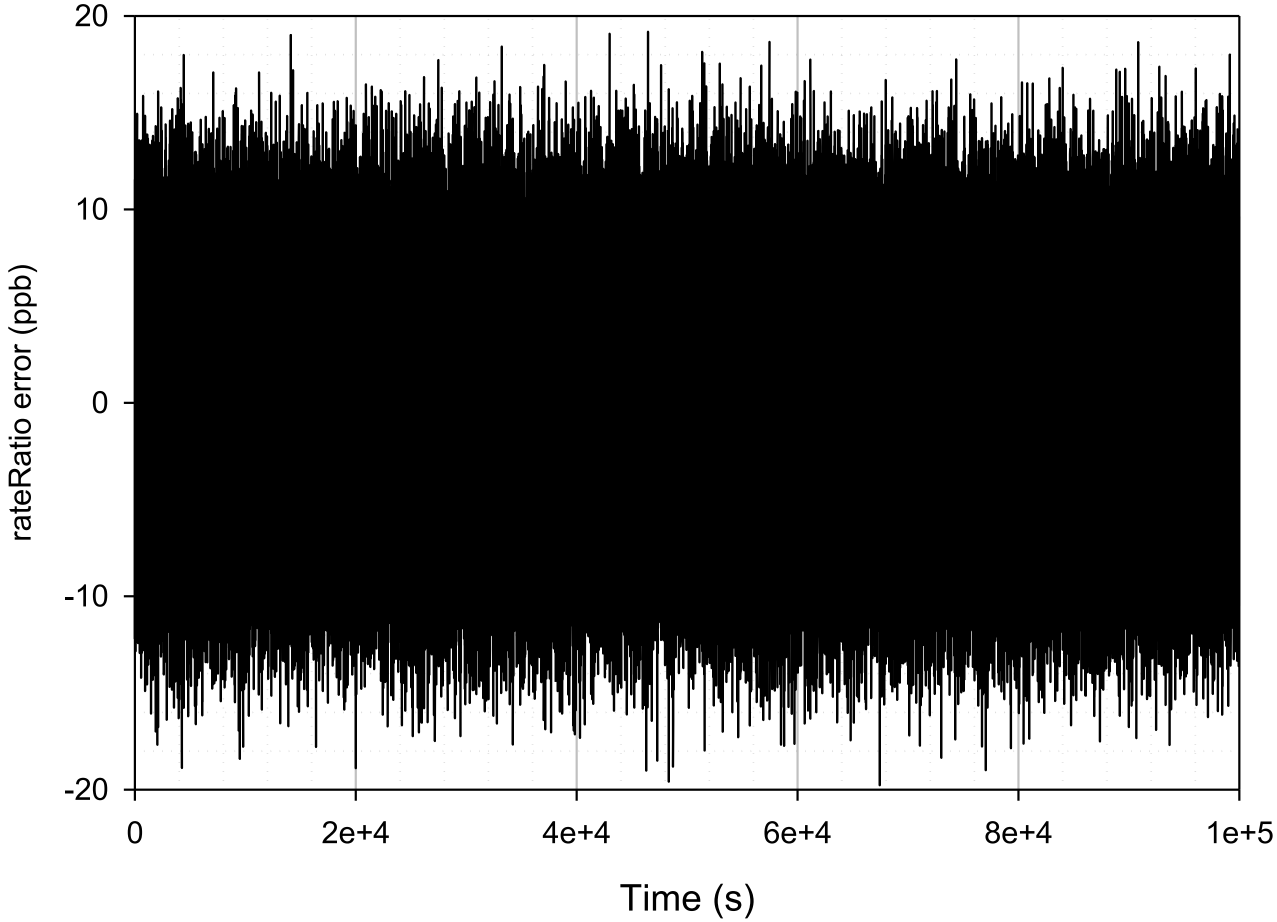


Plots for Case 1b – following 4 slides

Case 1b, Replication 1
preciseOriginTimestamp + correctionField - Working Clock at GM at transmission of Sync message
Node 3



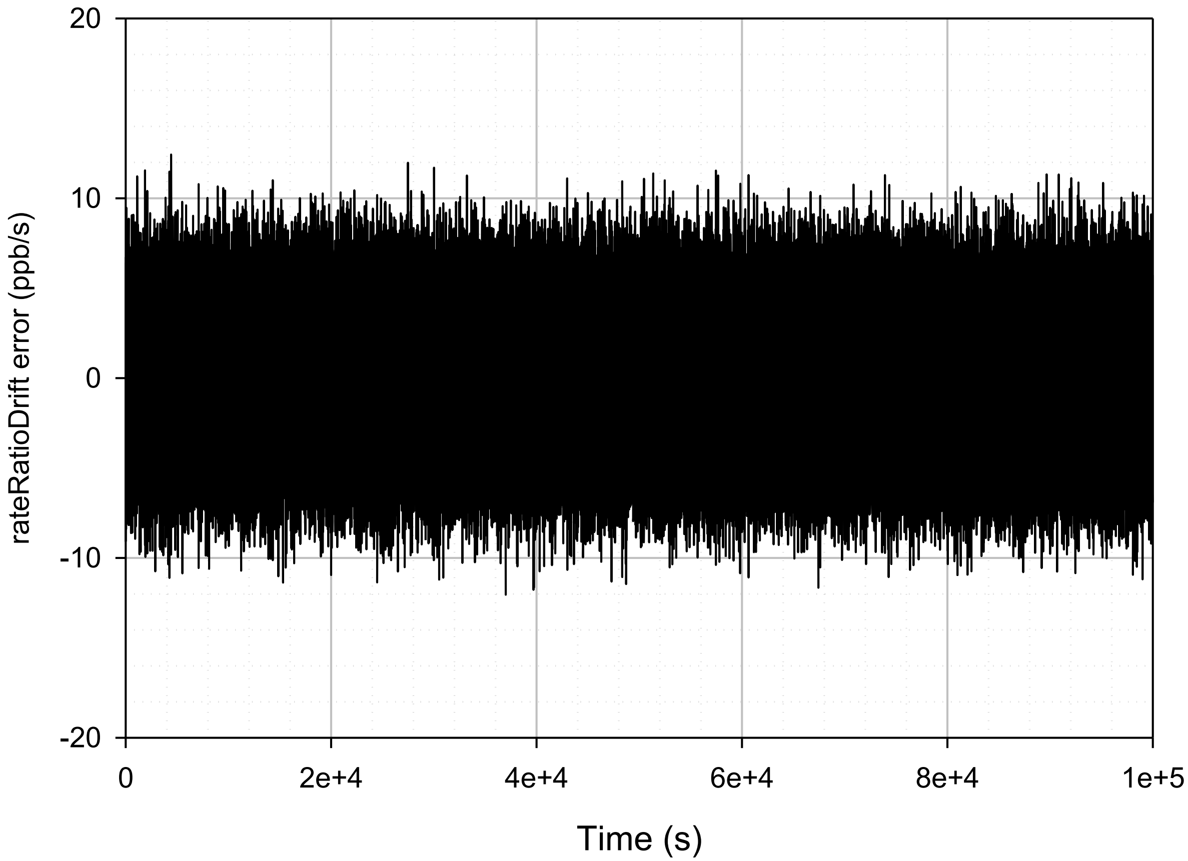
Case 1b, Replication 1
rateRatio field of transmitted Sync message by DUT minus actual rate ratio of DUT working clock relative to Working Clock at GM at transmission of Sync message
Node 3



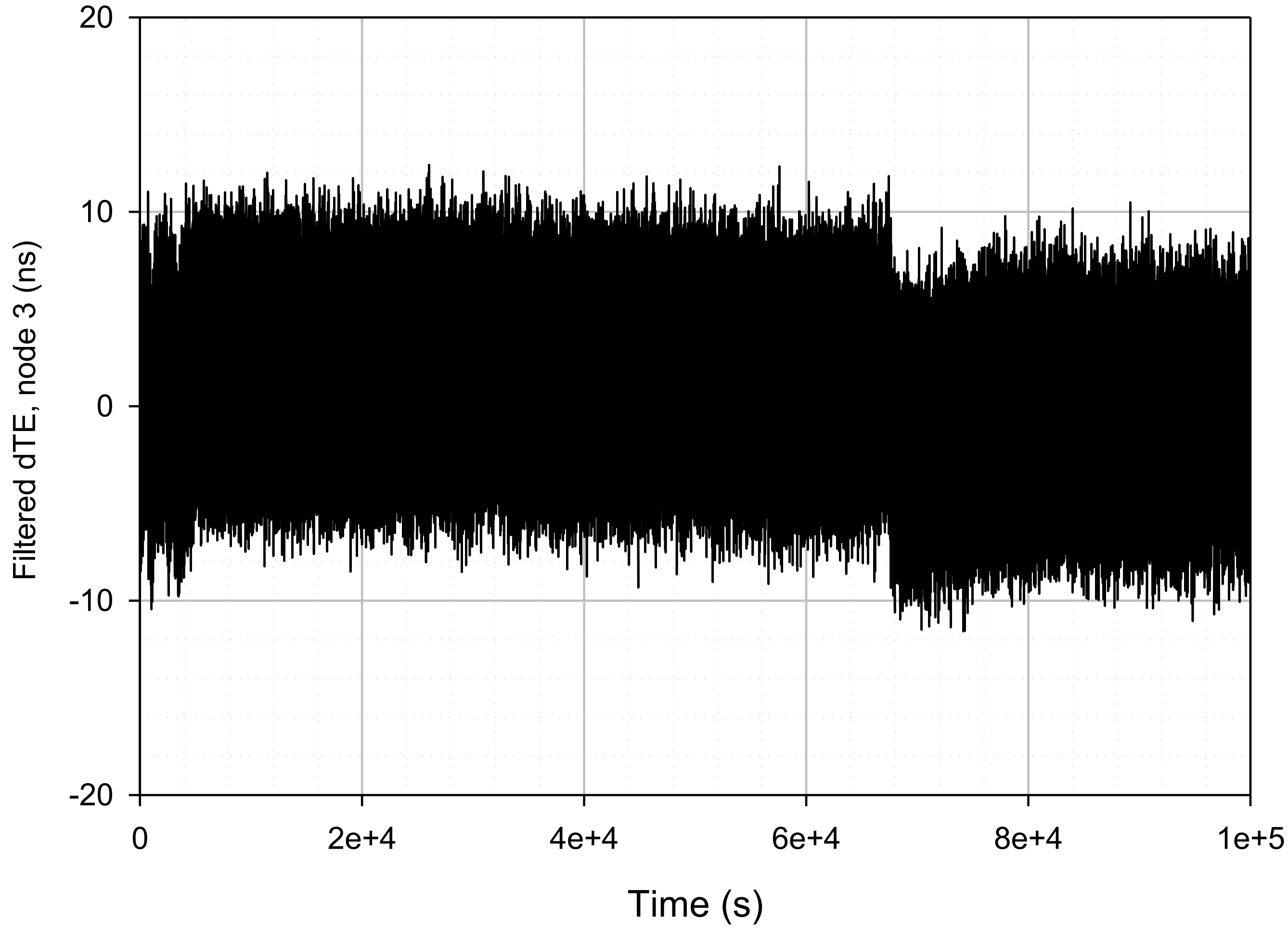
Case 1b, Replication 1

rateRatioDrift field of transmitted Sync message by DUT minus actual rate ratio drift rate of DUT working clock relative to Working Clock at GM at transmission of Sync message

Node 3

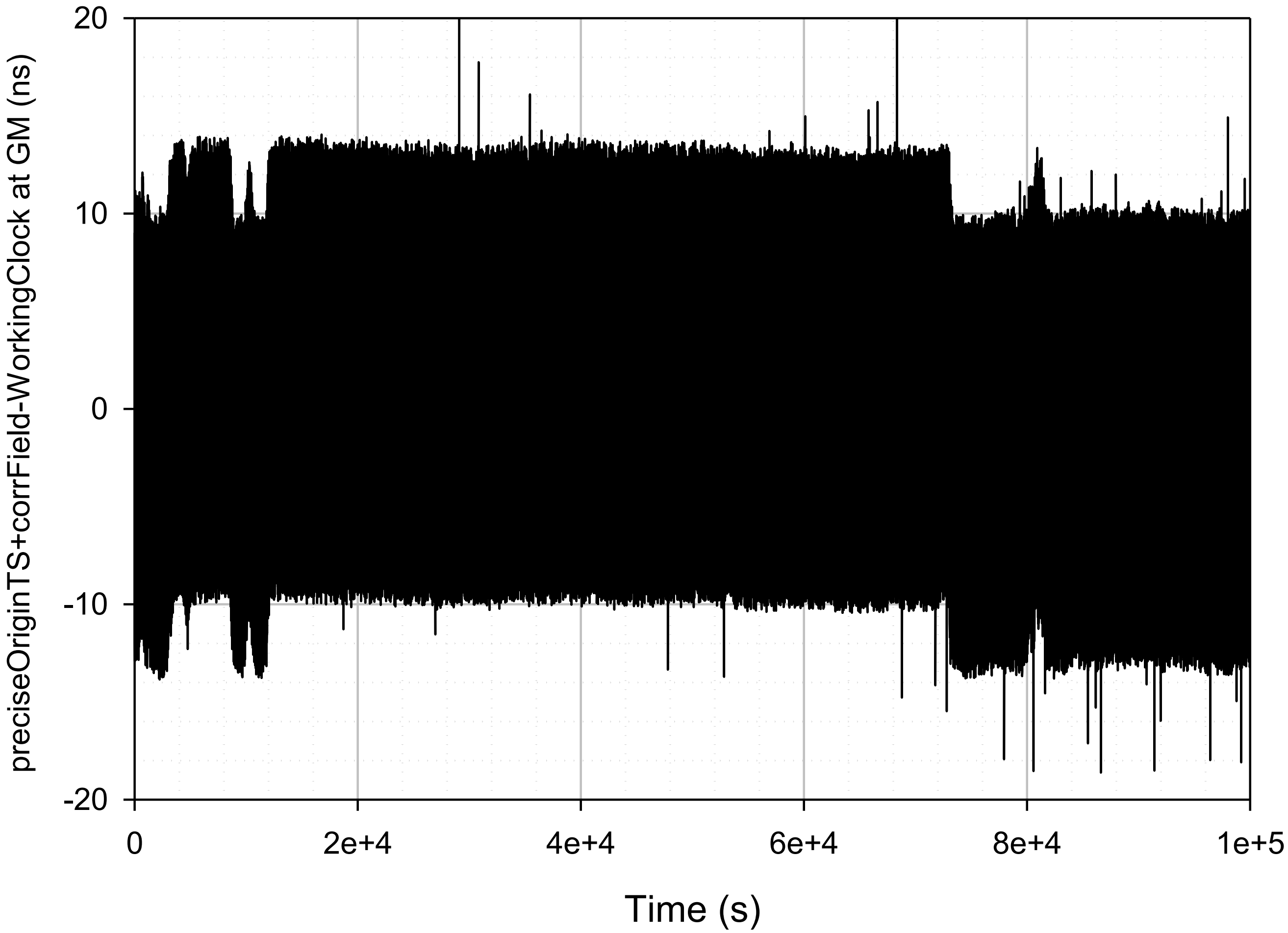


Case 1b, Replication 1
Filtered dTE (PTP End Instance), Node 3
Detail of 2 - 100000 s

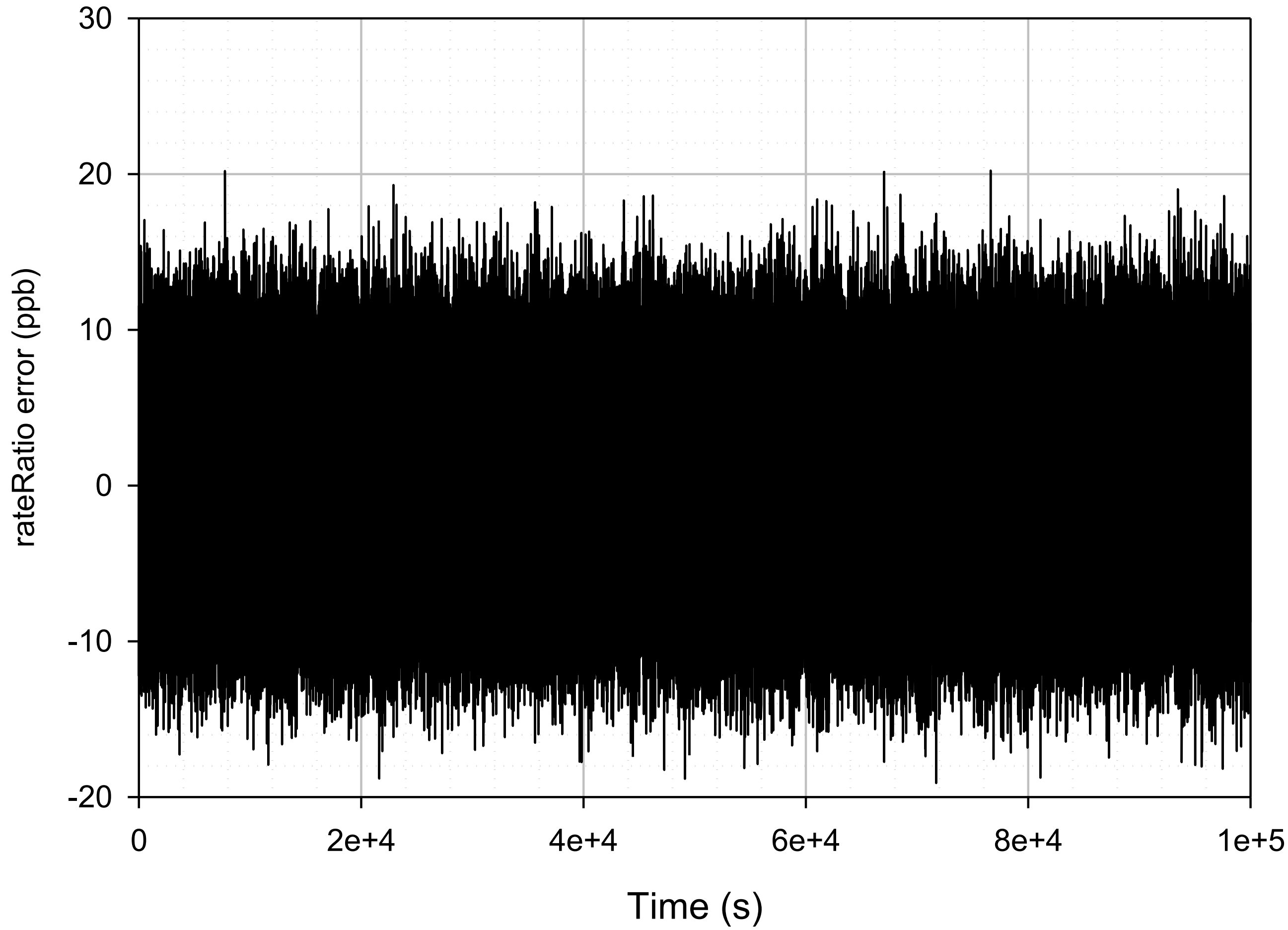


Plots for Case 1c - following 4 slides

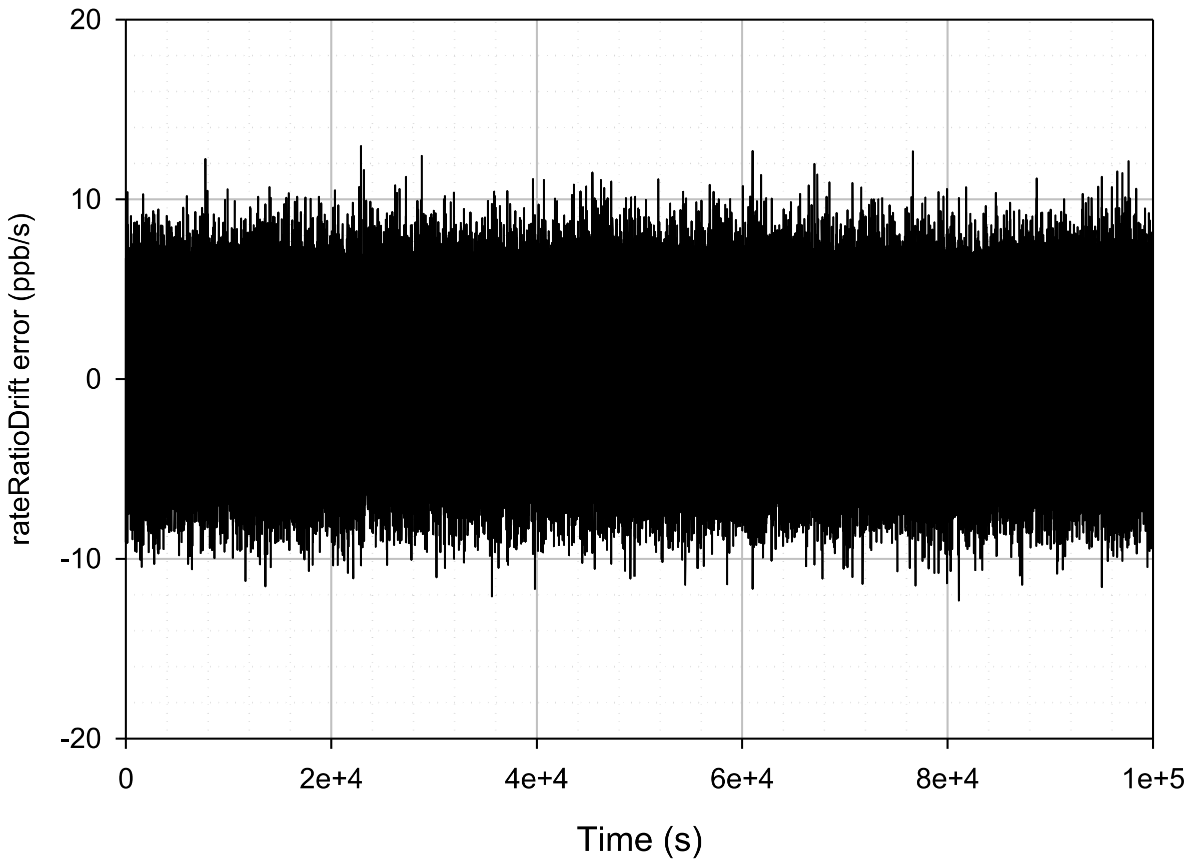
Case 1c, Replication 1
preciseOriginTimestamp + correctionField - Working Clock at GM at transmission of Sync message
Node 3



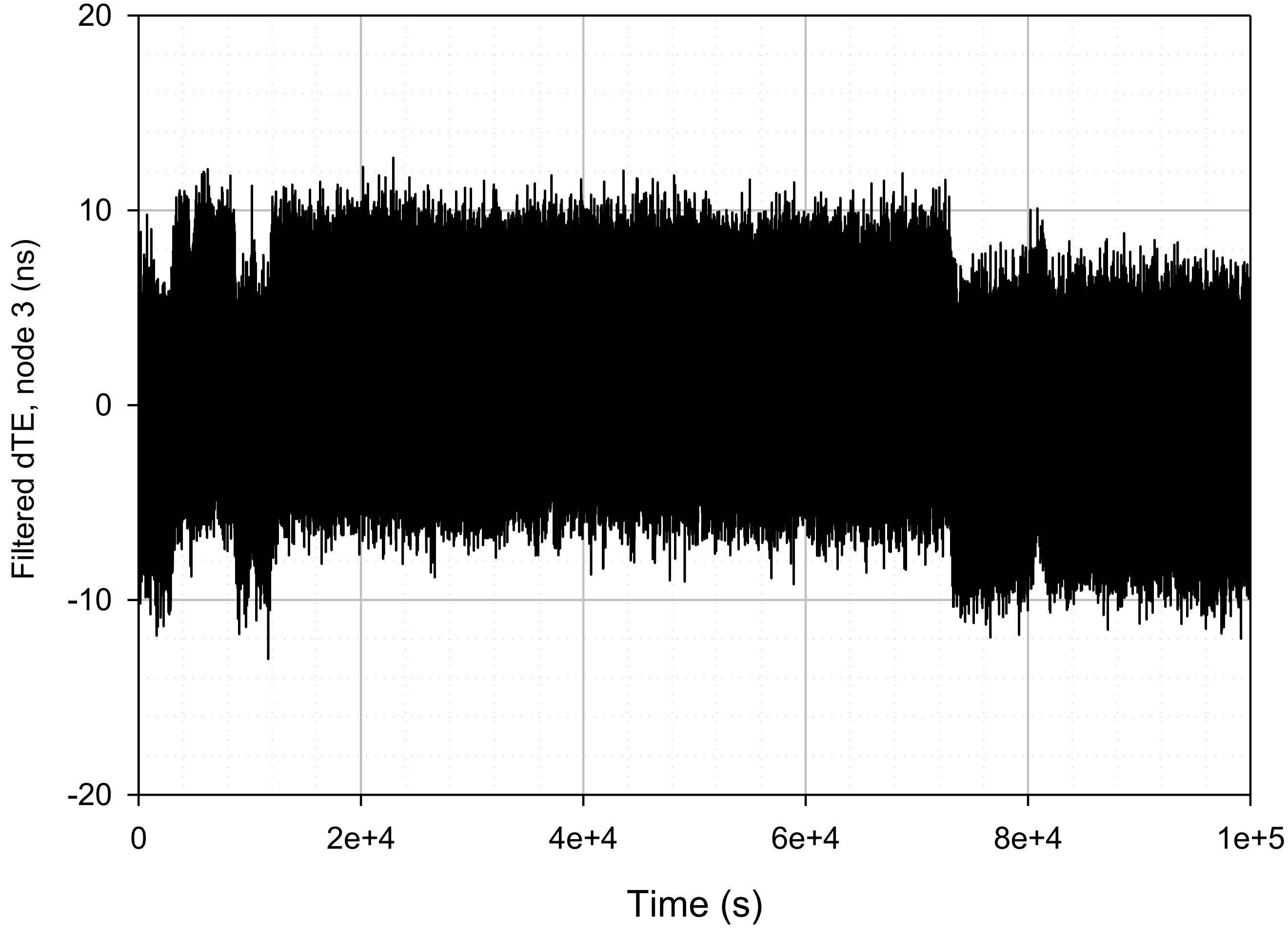
Case 1c, Replication 1
rateRatio field of transmitted Sync message by DUT minus actual rate ratio of DUT working clock relative to Working Clock at GM at transmission of Sync message
Node 3



Case 1c, Replication 1
rateRatioDrift field of transmitted Sync message by DUT minus actual rate ratio drift rate of DUT working clock relative to Working Clock at GM at transmission of Sync message
Node 3



Case 1c, Replication 1
Filtered dTE (PTP End Instance), Node 3
Detail of 2 - 100000 s



Experiment 1, 1b, and 1c Results

Mean Link Delay (ns)						
	Case 1		Case 1b		Case 1c	
Statistic computed over time	**Minimum over 300 replics**	**Maximum over 300 replics**	**Minimum over 300 replics**	**Maximum over 300 replics**	**Minimum over 300 replics**	**Maximum over 300 replics**
Minimum over time	451.946	455.994	451.973	456.022	451.935	455.974
5^{th} percentile over time	452.107	456.098	452.091	456.095	452.109	456.092
95^{th} percentile over time	452.373	456.340	452.310	456.326	452.371	456.347
Maximum over time	453.168	456.453	452.414	456.477	453.187	456.453
Mean over time	452.255	456.198	452.208	456.191	452.254	456.198
Standard Deviation over time	0.062229	1.92019	0.059989	1.93799	0.065517	1.92145

Experiment 1, 1b, and 1c Results

preciseOriginTimeStamp+correctionField-(Working Clock at GM), when Sync is transmitted (i.e., M) (ns) [Red values are requirements from 60802 Table 13]						
	Case 1		Case 1b		Case 1c	
Statistic computed over time	**Minimum over 300 replics**	**Maximum over 300 replics**	**Minimum over 300 replics**	**Maximum over 300 replics**	**Minimum over 300 replics**	**Maximum over 300 replics**
Minimum over time	-18.465 (±20 ns)	-9.593 (±20 ns)	-17.738	-9.552	-18.475	-9.593
5^{th} percentile over time	-8.671 (±10 ns)	-4.680 (±10 ns)	-8.709	-4.614	-8.670	-4.676
95^{th} percentile over time	4.693 (±10 ns)	8.673 (±10 ns)	4.643	8.689	4.693	8.669
Maximum over time	9.587 (±20 ns)	18.045 (±20 ns)	9.554	19.171	9.596	18.033
Mean over time	-1.973	2.008	-2.032	2.019	-1.974	2.008
Standard Deviation over time	3.990	4.449	3.993	4.453	3.990	4.449

Experiment 1, 1b, and 1c Results

preciseOriginTimeStamp+correctionField-(Working Clock at GM)-measured mean for the replication, when Sync is transmitted (i.e., M minus measured mean) (ns) [Red values are requirements from 60802 Table 13]						
	Case 1		Case 1b		Case 1c	
Statistic computed over time	**Minimum over 300 replics**	**Maximum over 300 replics**	**Minimum over 300 replics**	**Maximum over 300 replics**	**Minimum over 300 replics**	**Maximum over 300 replics**
Minimum over time	-19.448 ($\pm$20 ns)	-11.536 ($\pm$20 ns)	-18.774	-11.407	-19.456	-11.556
5^{th} percentile over time	-7.370 ($\pm$10 ns)	-6.644 ($\pm$10 ns)	--7.423	-6.633	-7.369	-6.645
95^{th} percentile over time	6.651 ($\pm$10 ns)	7.410 ($\pm$10 ns)	6.651	7.383	6.651	7.410
Maximum over time	11.512 ($\pm$20 ns)	18.361 ($\pm$20 ns)	11.561	18.951	11.523	18.392
Mean over time	-1.973	2.008	-2.032	2.019	-1.974	2.008
Standard Deviation over time	3.990	4.449	3.993	4.453	3.990	4.449

Experiment 1, 1b, and 1c Results

rateRatio field of Sync minus actual rate ratio, when Sync is sent (i.e., N) (ppb) [Red values are requirements from 60802 Table 13]						
	Case 1		Case 1b		Case 1c	
Statistic computed over time	**Minimum over 300 replics**	**Maximum over 300 replics**	**Minimum over 300 replics**	**Maximum over 300 replics**	**Minimum over 300 replics**	**Maximum over 300 replics**
Minimum over time	-20.798	-15.650	-21.518	-15.550	-20.799	-15.649
5^{th} percentile over time	-7.330	-6.993	-7.345	-6.377	-7.330	-6.993
95^{th} percentile over time	6.995	7.277	6.998	7.318	6.996	7.277
Maximum over time	15.395	21.973	15.587	21.380	15.395	21.973
Mean over time	-1.809×10^{-3} ($\pm$100 ppb)	1.587×10^{-3} ($\pm$100 ppb)	-9.910×10^{-4}	2.774×10^{-3}	-1.431×10^{-3}	1.964×10^{-3}
Standard Deviation over time	4.270 ($\pm$20 ppb)	4.415 ($\pm$20 ppb)	4.249	4.430	4.270	4.415

Experiment 1, 1b, and 1c Results

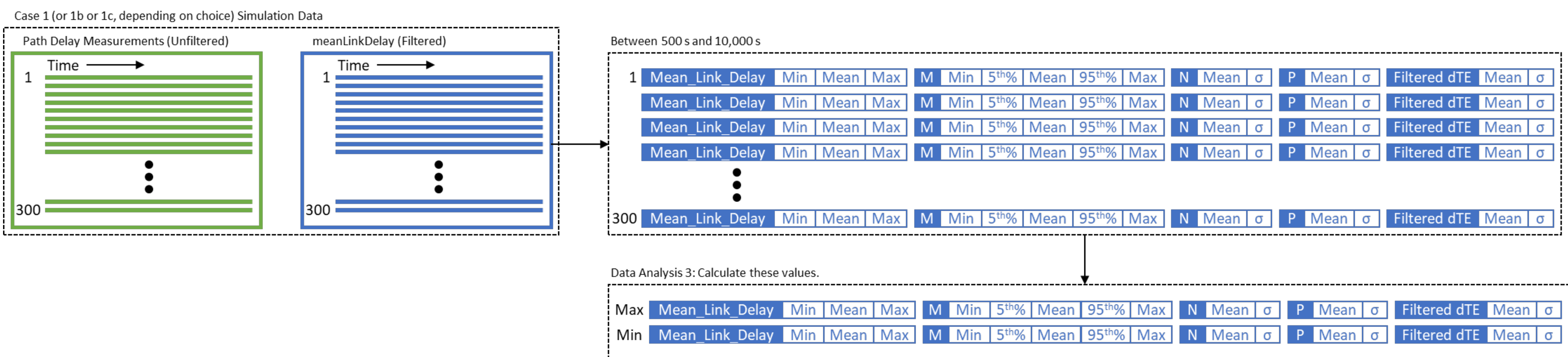
rateRatioDrift field of Sync minus actual rate ratio drift, when Sync is sent (i.e., P) (ppb/s)						
	Case 1		**Case 1b**		**Case 1c**	
Statistic computed over time	**Minimum over 300 replics**	**Maximum over 300 replics**	**Minimum over 300 replics**	**Maximum over 300 replics**	**Minimum over 300 replics**	**Maximum over 300 replics**
Minimum over time	-13.659	-9.481	-13.875	-9.430	-13.658	-9.479
5^{th} percentile over time	-4.520	-4.341	-4.532	-4.313	-4.519	-4.340
95^{th} percentile over time	4.331	4.531	4.320	4.531	4.332	4.532
Maximum over time	9.610	13.878	9.669	13.717	9.609	13.879
Mean over time	-1.093×10^{-3} ($\pm$100 ppb/s)	9.424×10^{-4} ($\pm$100 ppb/s)	-1.414×10^{-3}	9.102×10^{-4}	-8.399×10^{-4}	1.195×10^{-3}
Standard Deviation over time	2.641 ($\pm$20 ppb/s)	2.739 ($\pm$20 ppb/s)	2.629	2.747	2.641	2.739

Experiment 1, 1b, and 1c Results

Filtered dTE (ns) [Red values are requirements from 60802 Table 14]						
	Case 1		Case 1b		Case 1c	
Statistic computed over time	**Minimum over 300 replics**	**Maximum over 300 replics**	**Minimum over 300 replics**	**Maximum over 300 replics**	**Minimum over 300 replics**	**Maximum over 300 replics**
Minimum over time	-13.904 (±15)	-7.755 (±15)	-13.871	-8.096	-13.894	-7.782
5th percentile over time	-6.411 (±15)	-2.449 (±15)	-6.431	-2.375	-6.410	-2.450
95th percentile over time	2.403 (±15)	6.383 (±15)	2.370	6.423	2.403	6.385
Maximum over time	8.183 (±15)	14.021 (±15)	8.117	13.662	8.192	14.042
Mean over time	-1.958 (±15)	1.975 (±15)	-2.016	1.995	-1.959	1.975
Standard Deviation over time	2.658	3.272	2.658	3.315	2.659	3.273

Experiments 2, 3, and 4 Data Analysis

- The quantities computed and data analyses for Experiments 2 and 3 are the same as for Experiment 1, data analysis 3, as described in [9]; for convenience, the description on slides 57 and 58 is repeated here
- For each of the 300 replications, calculate the following statistics over time for filtered mean link delay, M, N, P, and filtered dTE:
  - Minimum, 5th percentile, 95th percentile, maximum, mean, standard deviation
  - For each of the above statistics, compute the minimum and maximum value over the 300 replications (see figure below, which is taken from[10])

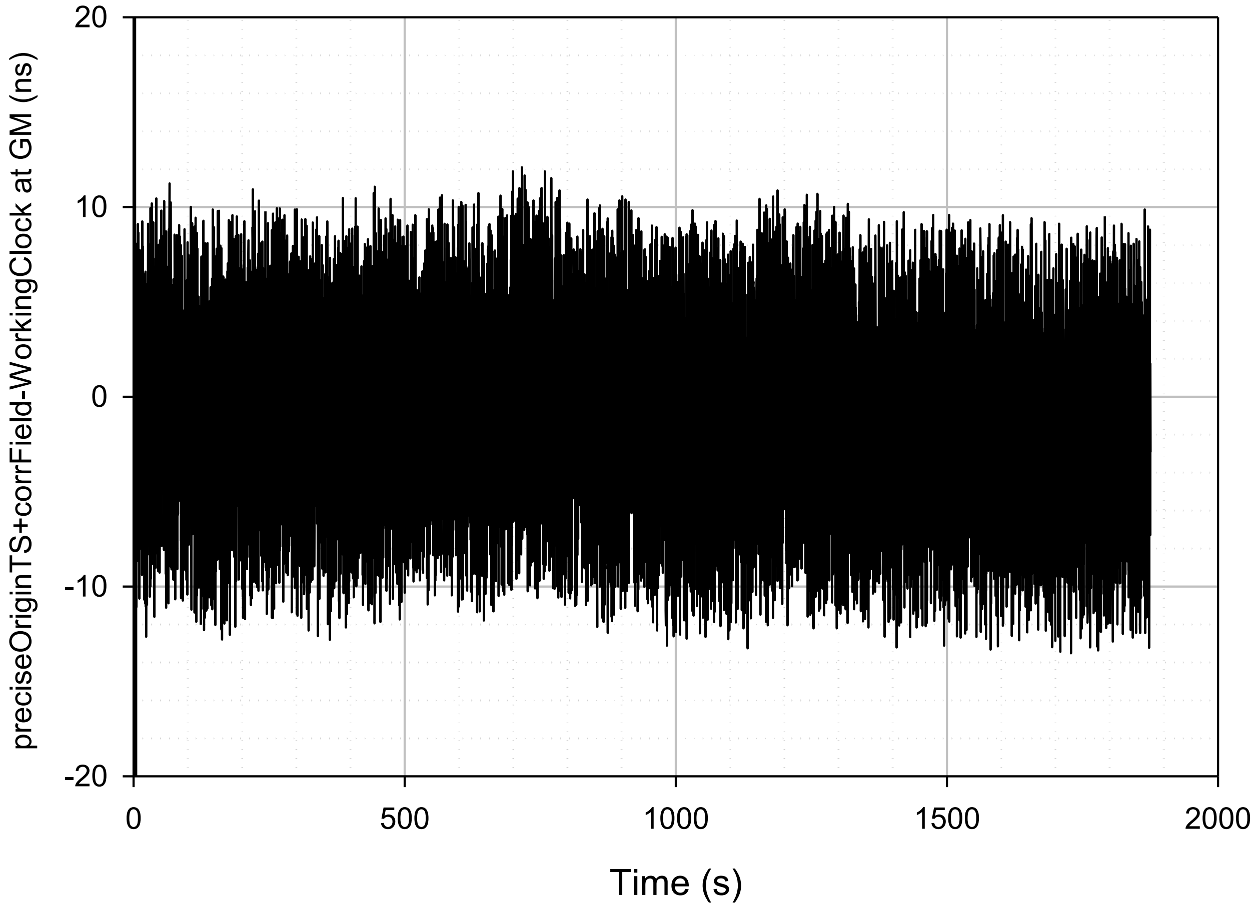


Experiments 2, 3, and 4 Data Analysis - 2

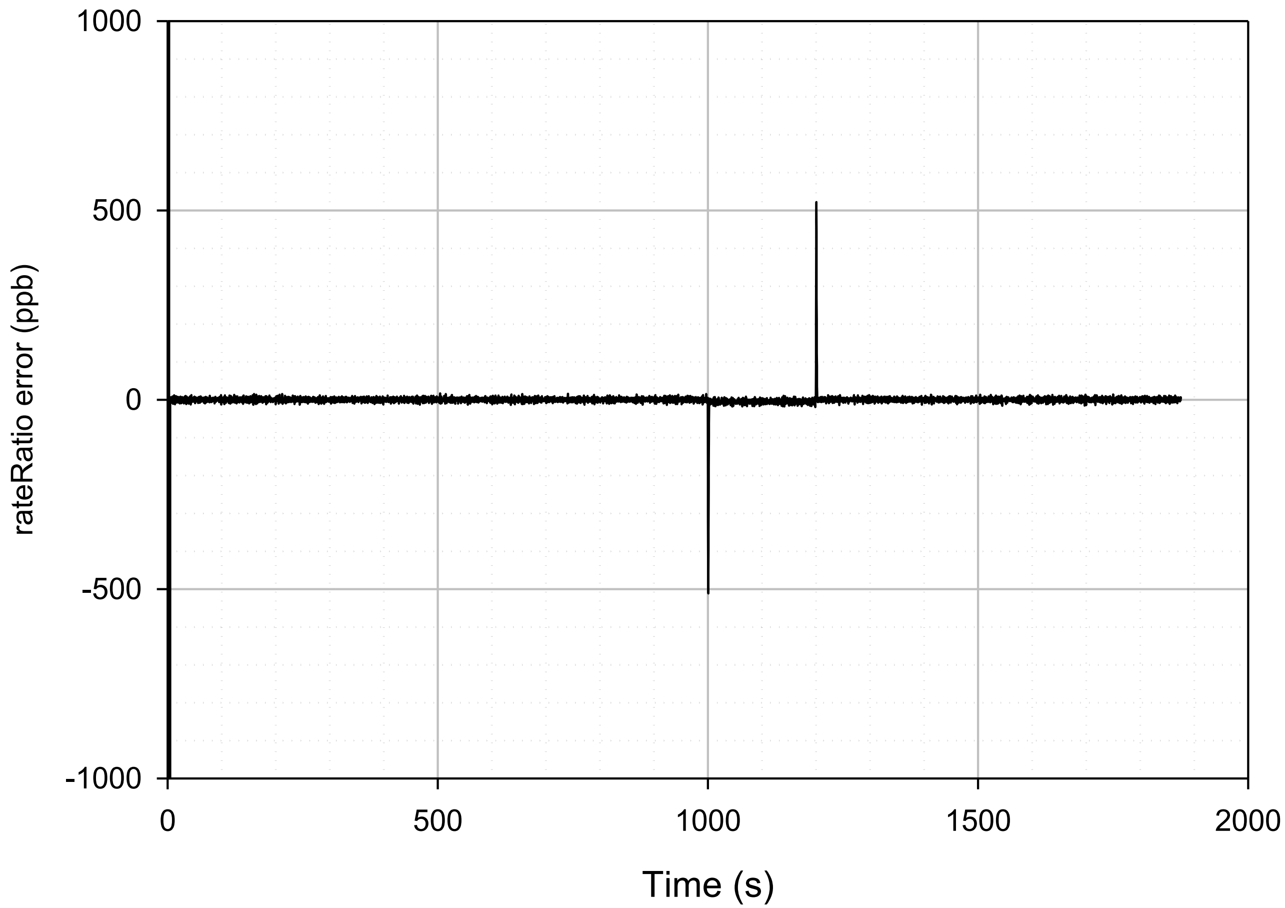
- The following plots are generated for Replication 1, for each of cases 2 and 3 (in some cases, 2 plots are given for the same result, one that shows overall behavior including transients when clock drift starts and stops, and one that zooms in on detail but does not show transients on the scale of the plot
  - M: preciseOriginTimestamp + correctionField – (Working Clock at GM), at node 3, when Sync is sent by node 3
  - N: rateRatio field of Sync message minus actual rateRatio, at node 3, when Sync is sent by node 3
  - P: rateRatioDrift field of Drift_Tracking TLV minus actual rate ratio drift, at node 3, when Sync is sent by node 3
  - Filtered dTE at node 3
- Following the plots, tables of numerical results are provided for minimum and maximum over 300 replications for the above statistics over time of mean link delay after filtering, M, N, P, and filtered dTE

Plots for Case 2 - following 7 slides

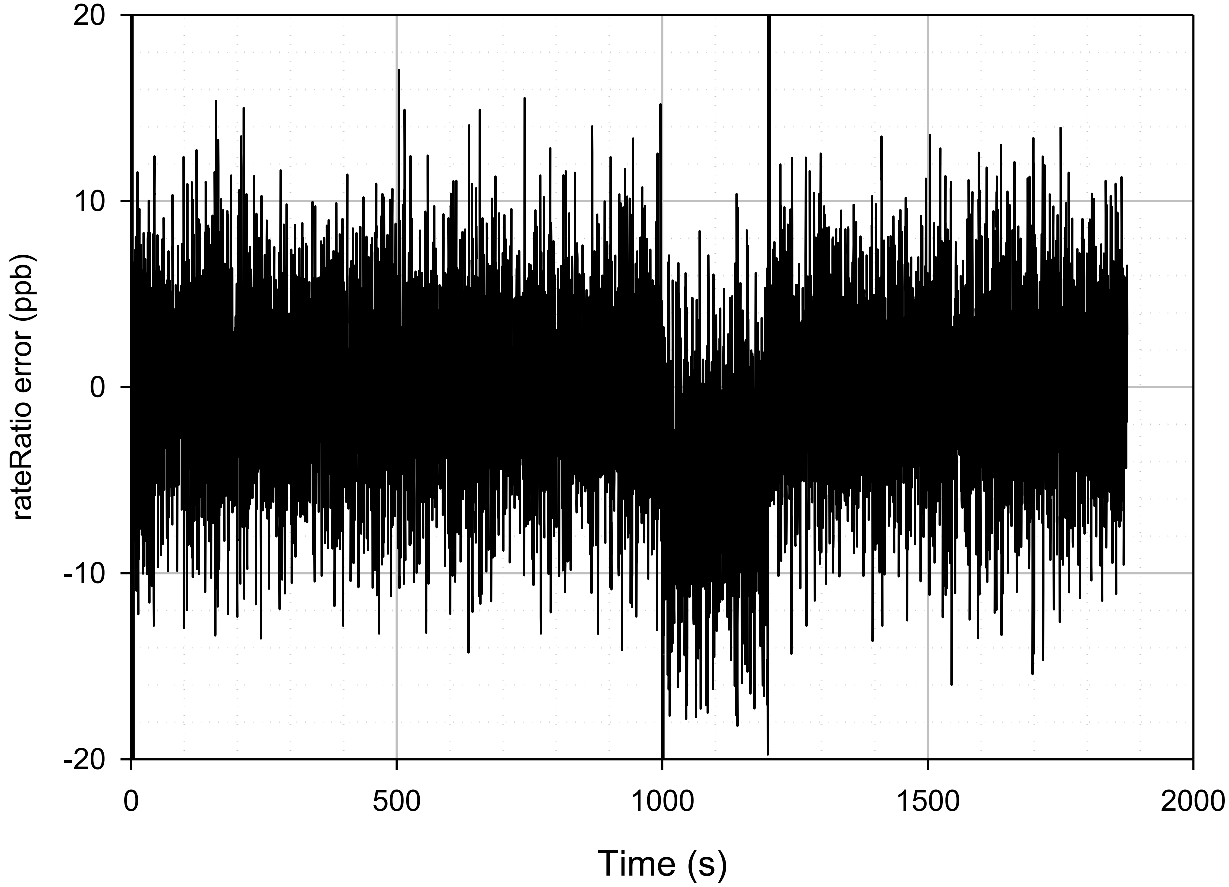
Case 2, Replication 1
preciseOriginTimestamp + correctionField - Working Clock at GM at transmission of Sync message
Detail of initial transient not shown on scale of plot
Node 3



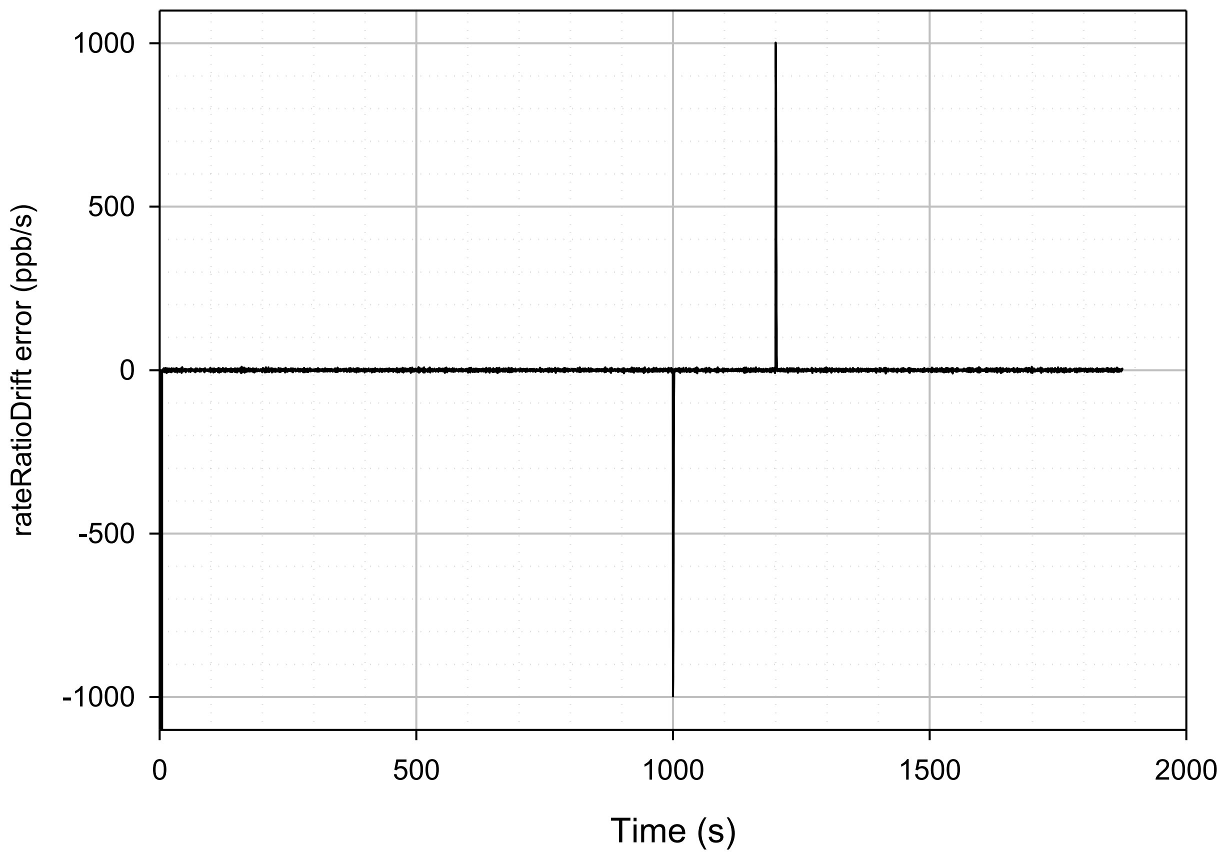
Case 2, Replication 1
rateRatio field of transmitted Sync message by DUT minus actual rate ratio of DUT working clock relative to Working Clock at GM at transmission of Sync message
Detail of initial transient not shown on scale of plot
Node 3



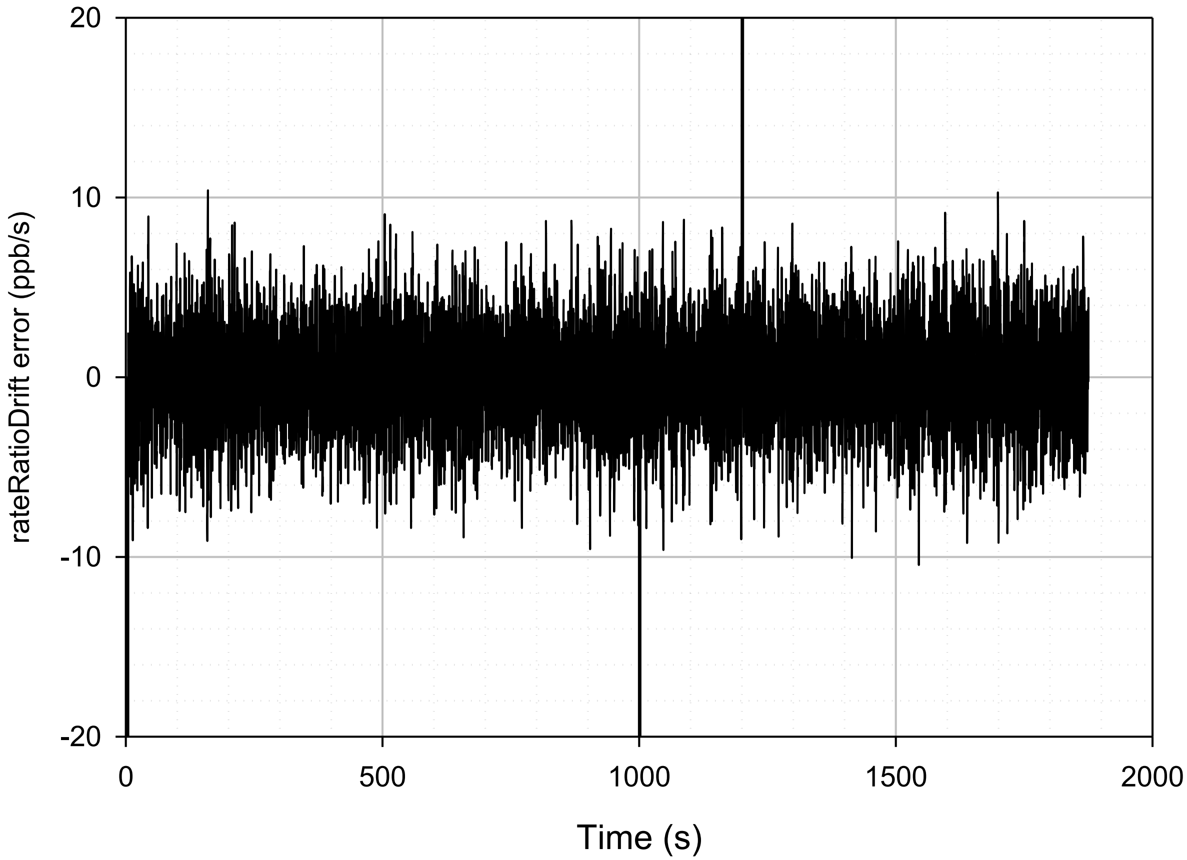
Case 2, Replication 1
rateRatio field of transmitted Sync message by DUT minus actual rate ratio of DUT working clock relative to Working Clock at GM at transmission of Sync message
Detail of initial transient and transients when clock drift starts and stops not shown on scale of plot
Node 3



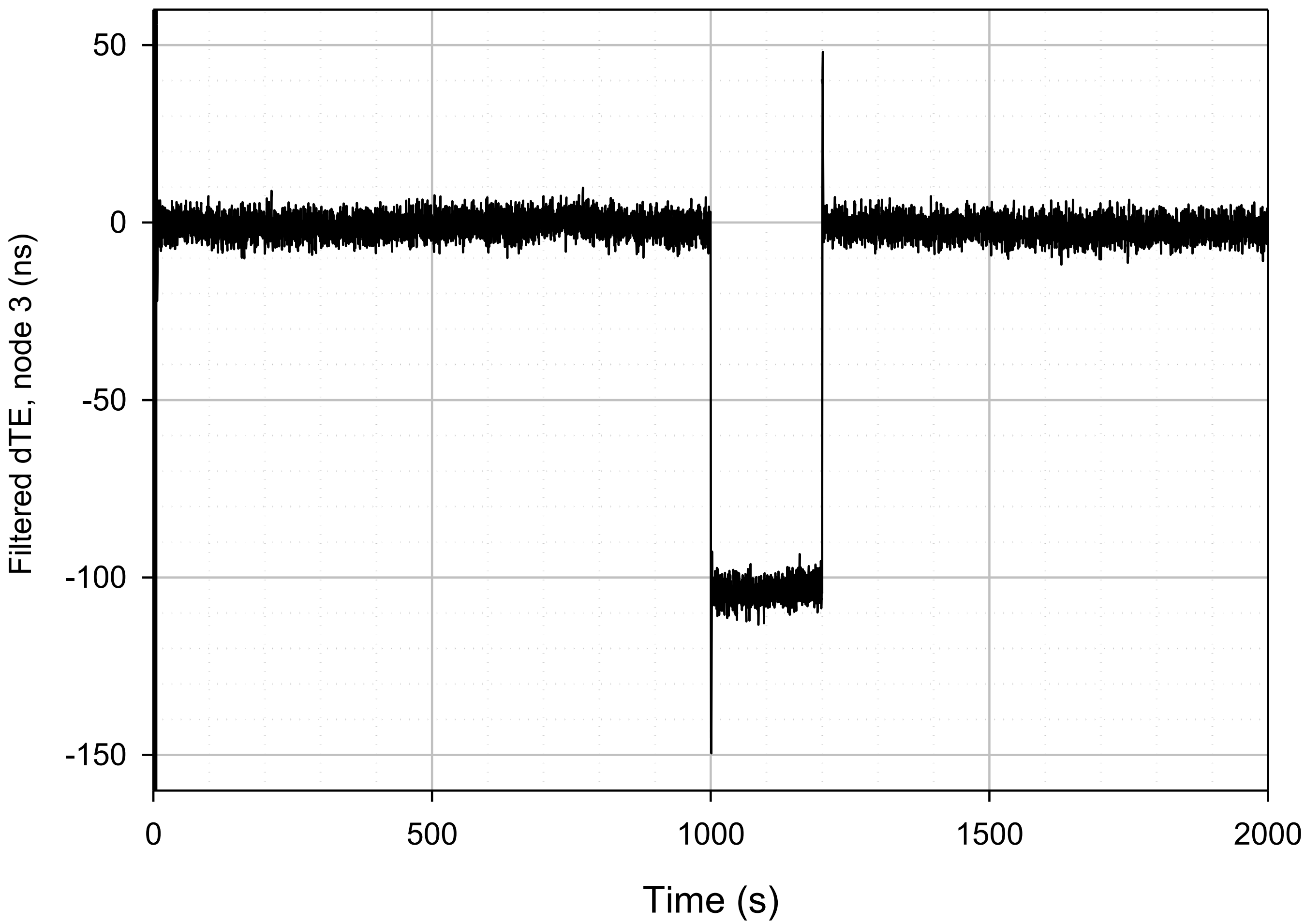
Case 2, Replication 1
rateRatioDrift field of transmitted Sync message by DUT minus actual rate ratio drift rate of DUT working clock relative to Working Clock at GM at transmission of Sync message
Detail of initial transient not shown on scale of plot
Node 3



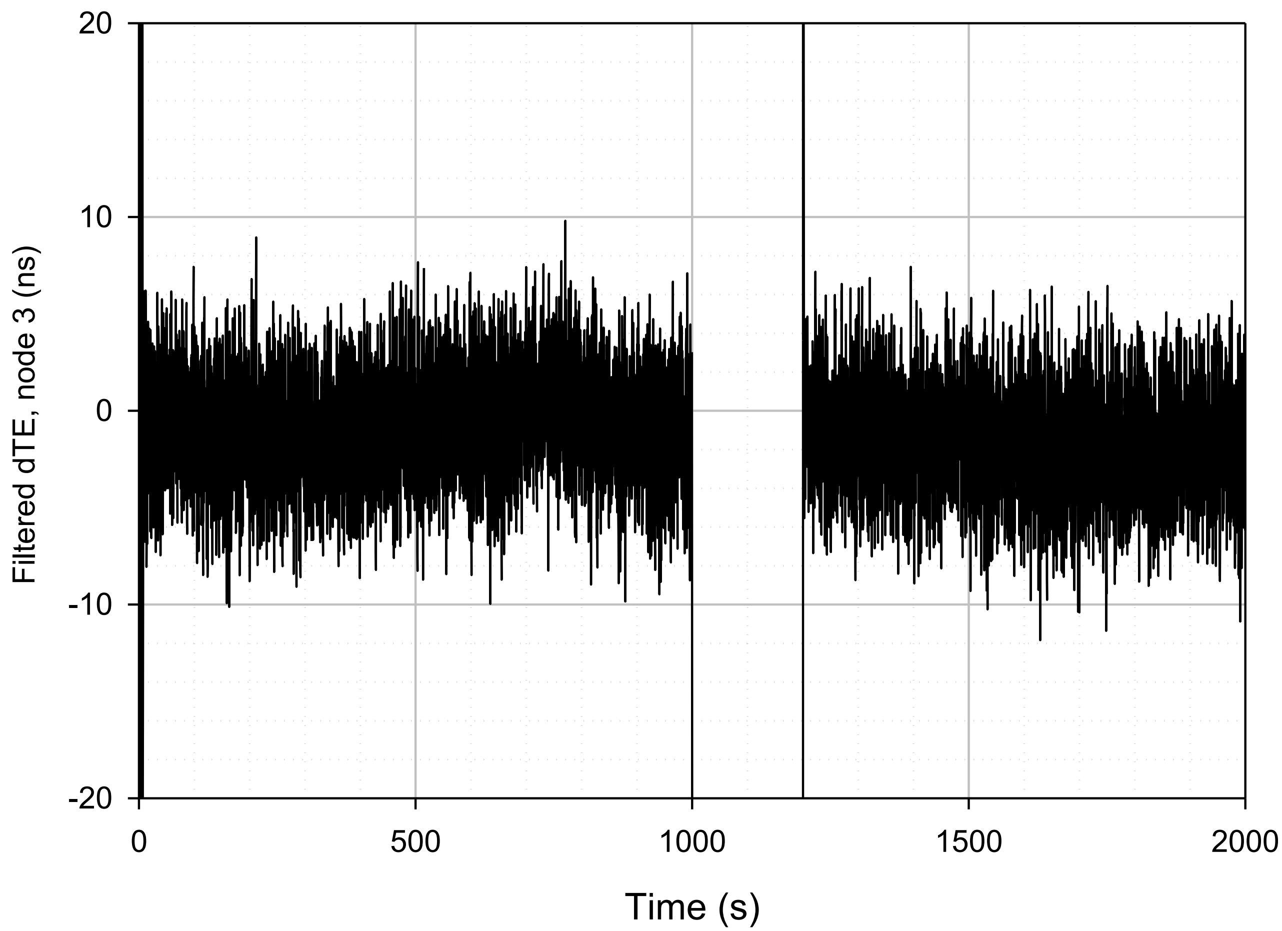
Case 2, Replication 1
rateRatioDrift field of transmitted Sync message by DUT minus actual rate ratio drift rate of DUT working clock relative to Working Clock at GM at transmission of Sync message
Detail of initial transient and transients when clock drift starts and stops not shown on scale of plot
Node 3



Case 2, Replication 1
Filtered dTE (PTP End Instance), Node 3
Detail of initial transient not shown on scale of plot

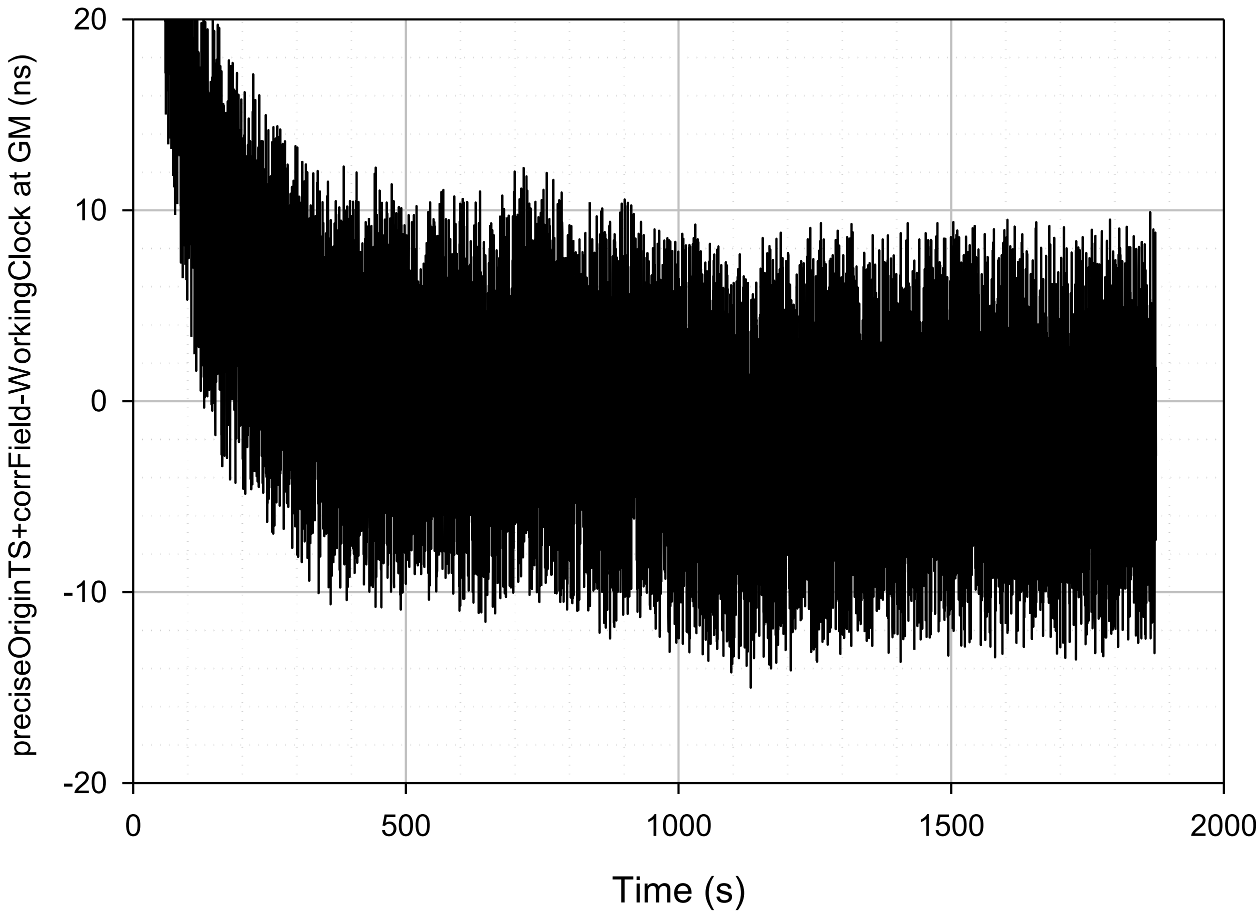


Case 2, Replication 1
Filtered dTE (PTP End Instance), Node 3
Detail of initial transient, period of clock drift, and transients when clock drift starts and stops not shown on scale of plot

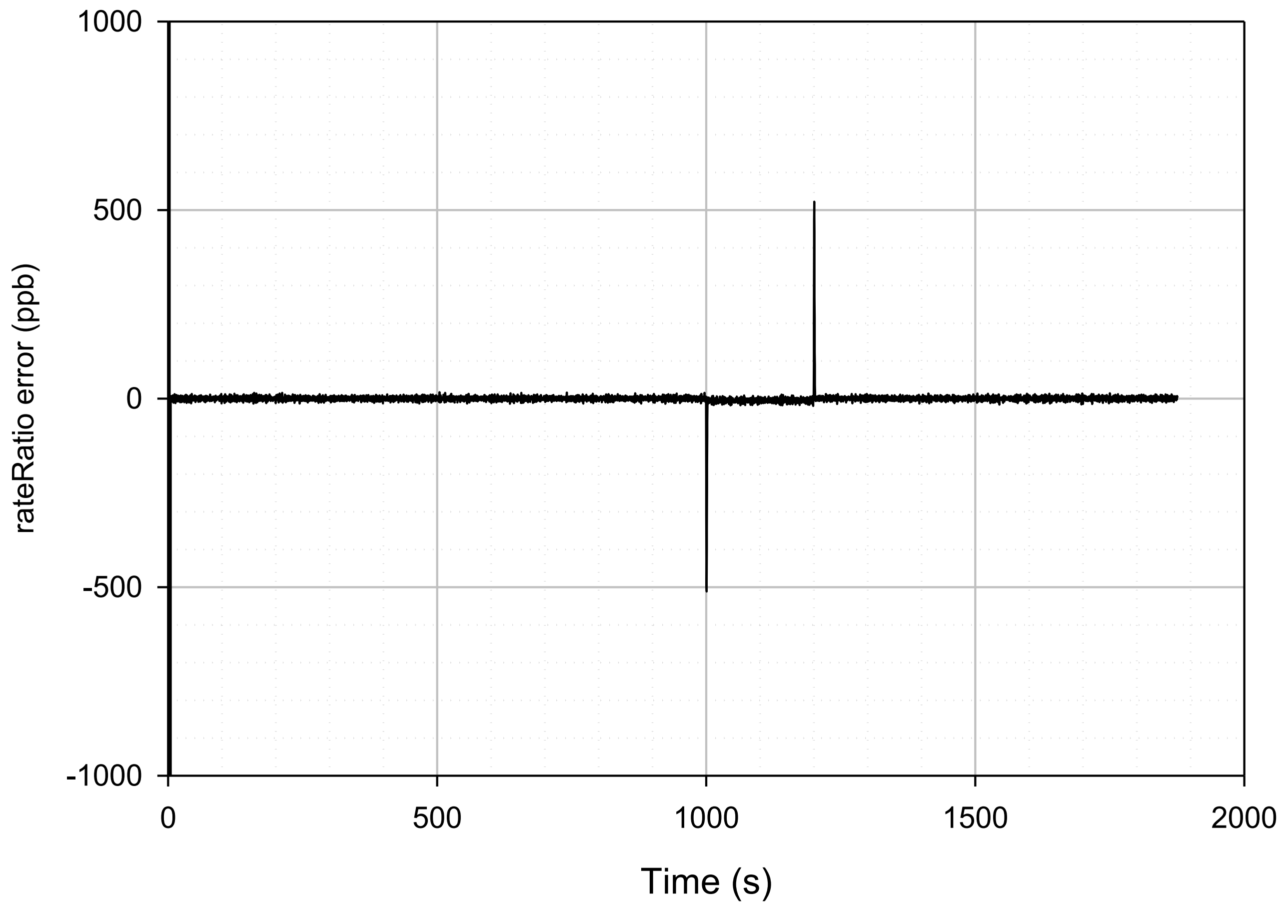


Plots for Case 3 – following 7 slides

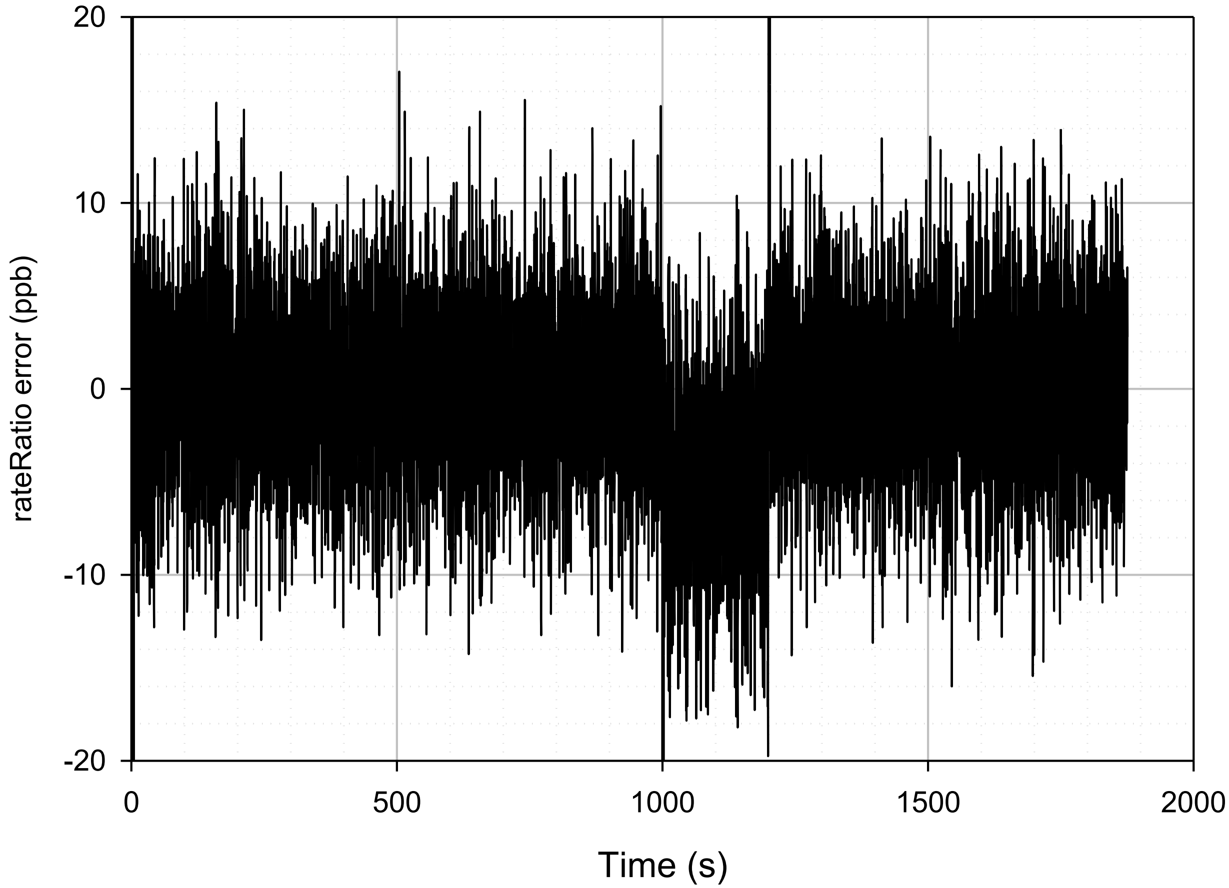
Case 3, Replication 1
preciseOriginTimestamp + correctionField - Working Clock at GM at transmission of Sync message
Full detail of initial transient not shown on scale of plot
Node 3



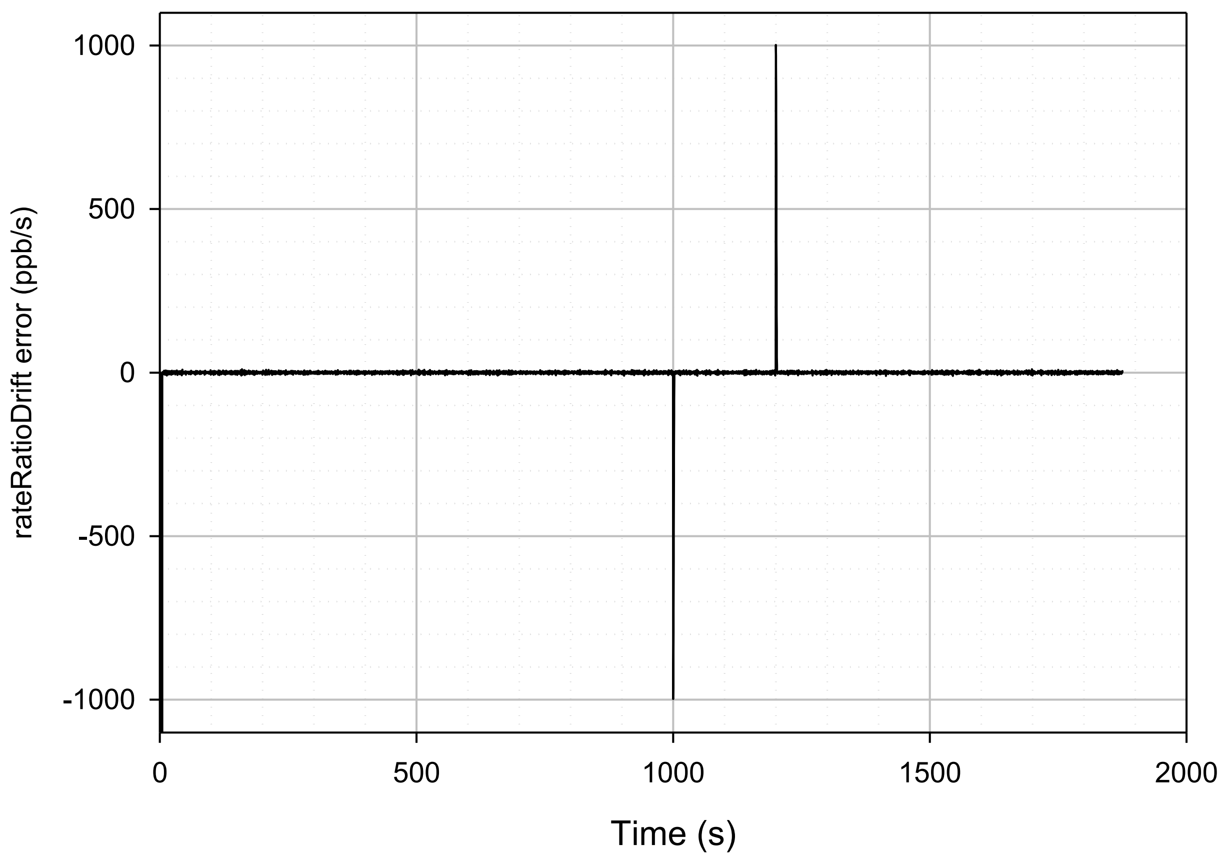
Case 3, Replication 1
rateRatio field of transmitted Sync message by DUT minus actual rate ratio of DUT working clock relative to Working Clock at GM at transmission of Sync message
Detail of initial transient not shown on scale of plot
Node 3



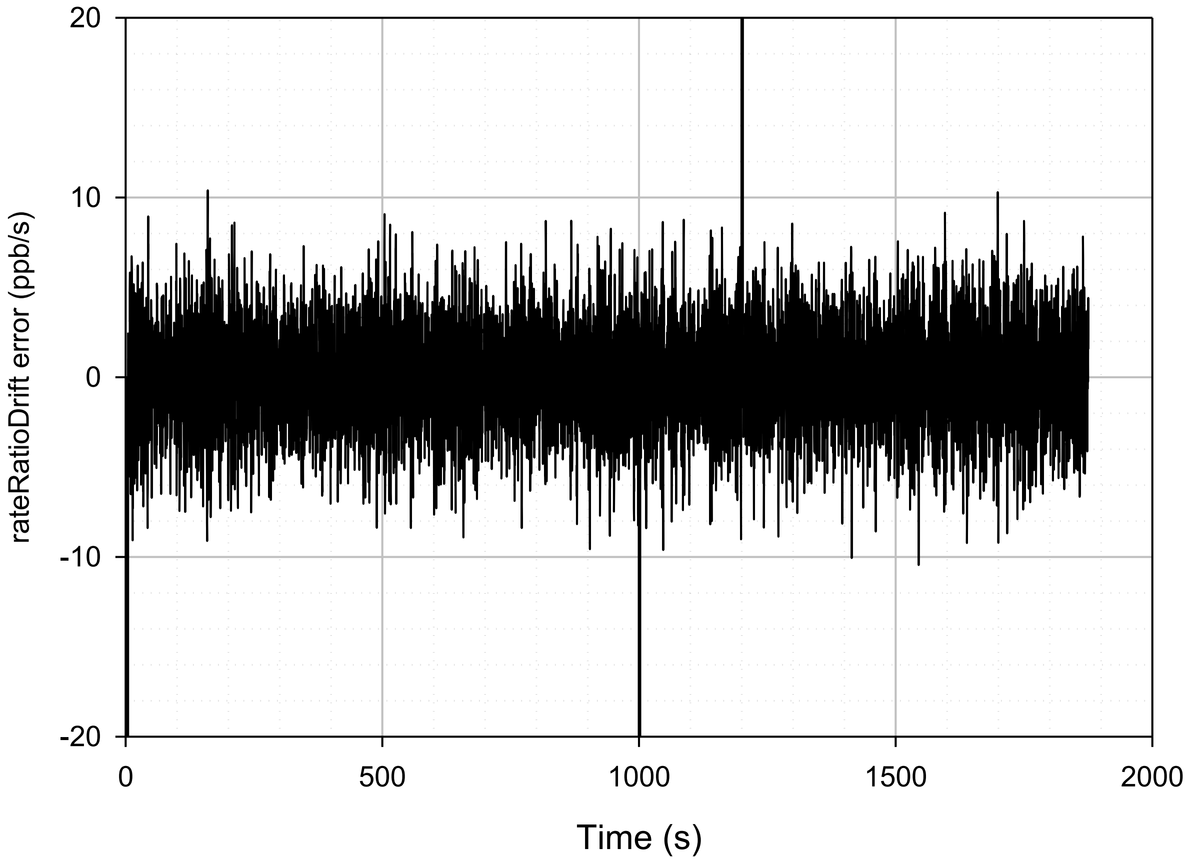
Case 3, Replication 1
rateRatio field of transmitted Sync message by DUT minus actual rate ratio of DUT working clock relative to Working Clock at GM at transmission of Sync message
Detail of initial transient and transients when clock drift starts and stops not shown on scale of plot
Node 3



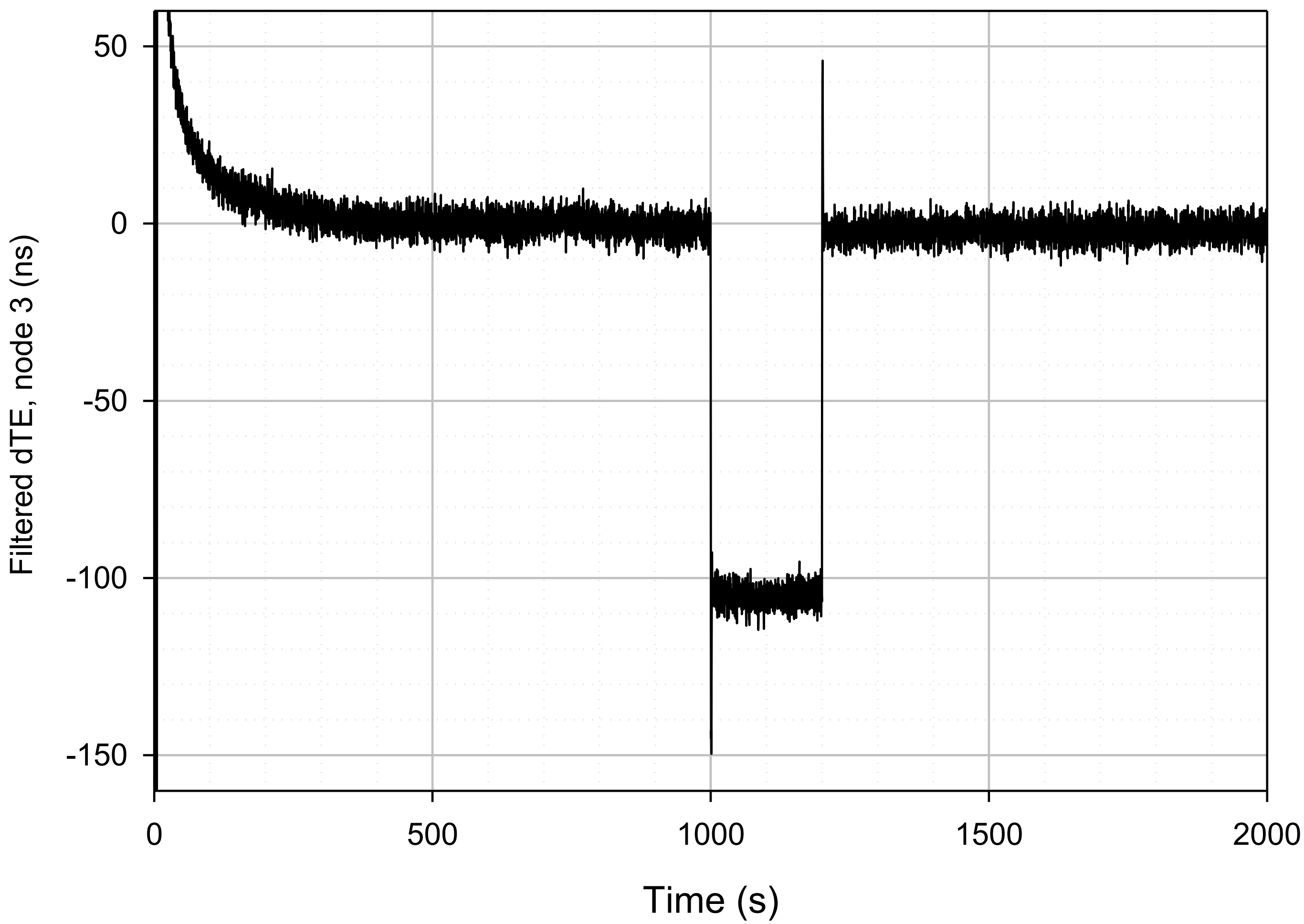
Case 3, Replication 1
rateRatioDrift field of transmitted Sync message by DUT minus actual rate ratio drift rate of DUT working clock relative to Working Clock at GM at transmission of Sync message
Detail of initial transient not shown on scale of plot
Node 3



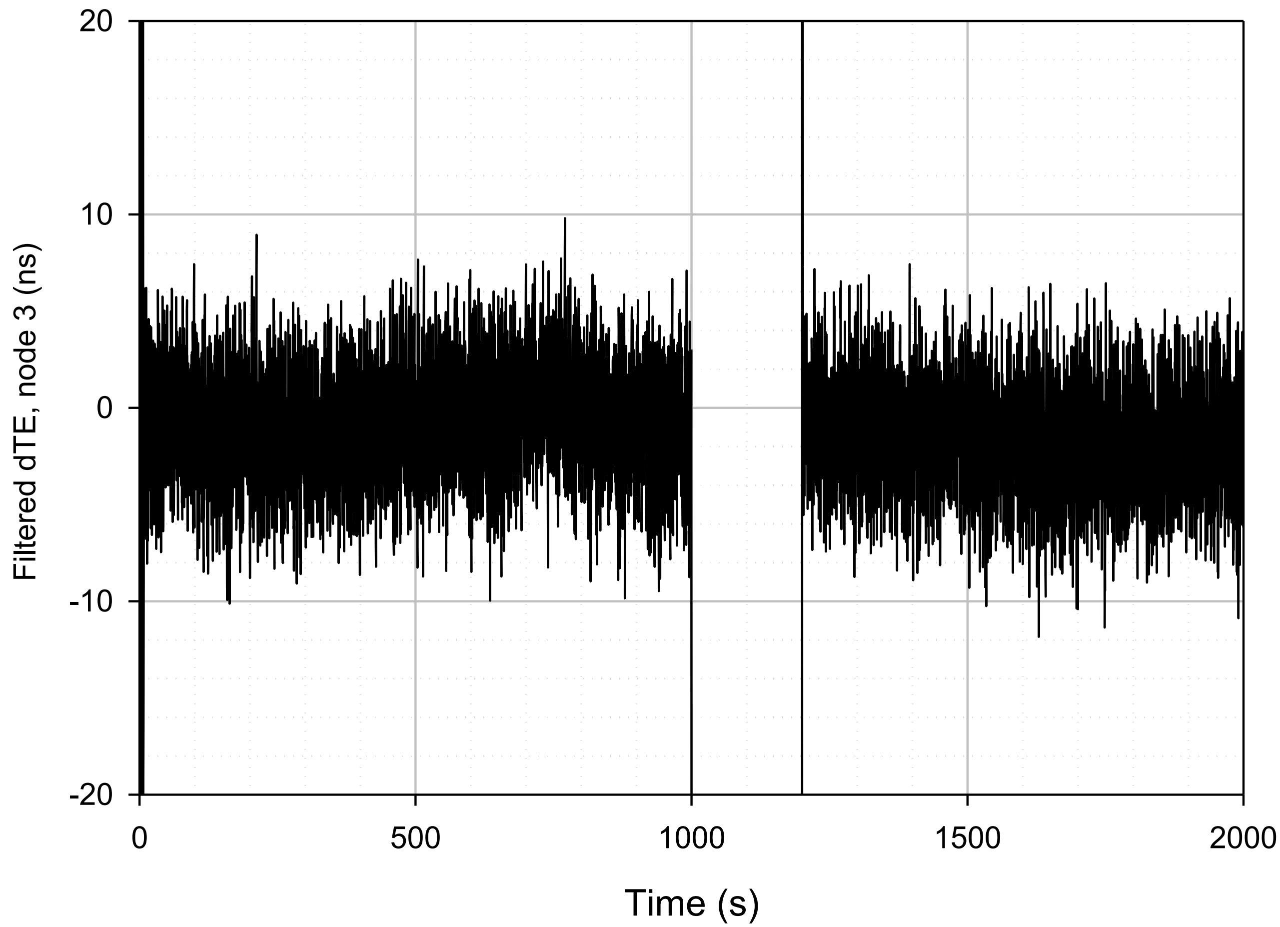
Case 3, Replication 1
rateRatioDrift field of transmitted Sync message by DUT minus actual rate ratio drift rate of DUT working clock relative to Working Clock at GM at transmission of Sync message
Detail of initial transient and transients when clock drift starts and stops not shown on scale of plot
Node 3



Case 3, Replication 1
Filtered dTE (PTP End Instance), Node 3
Full detail of initial transient not shown on scale of plot

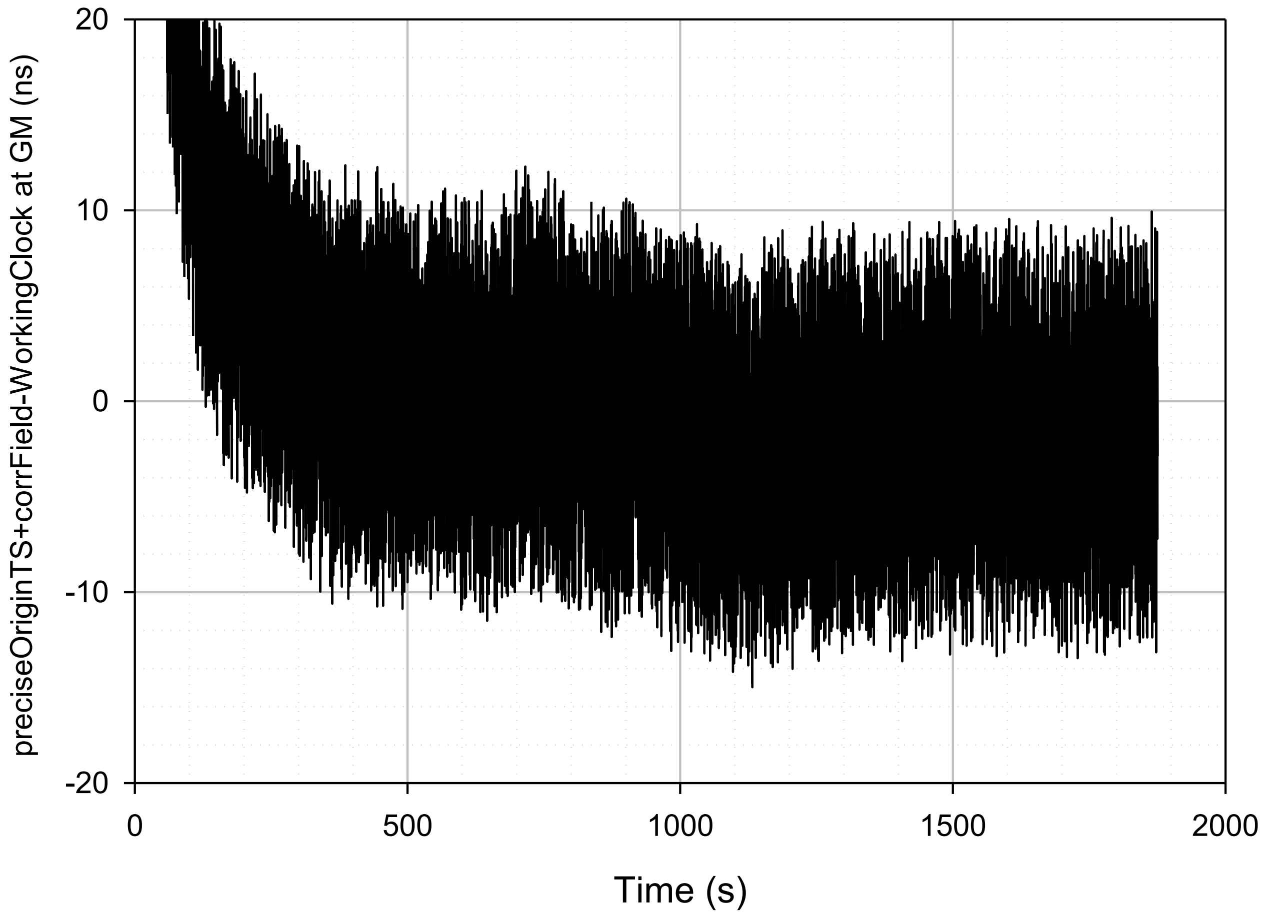


Case 3, Replication 1
Filtered dTE (PTP End Instance), Node 3
Detail of initial transient, period of clock drift, and transients when clock drift starts and stops not shown on scale of plot

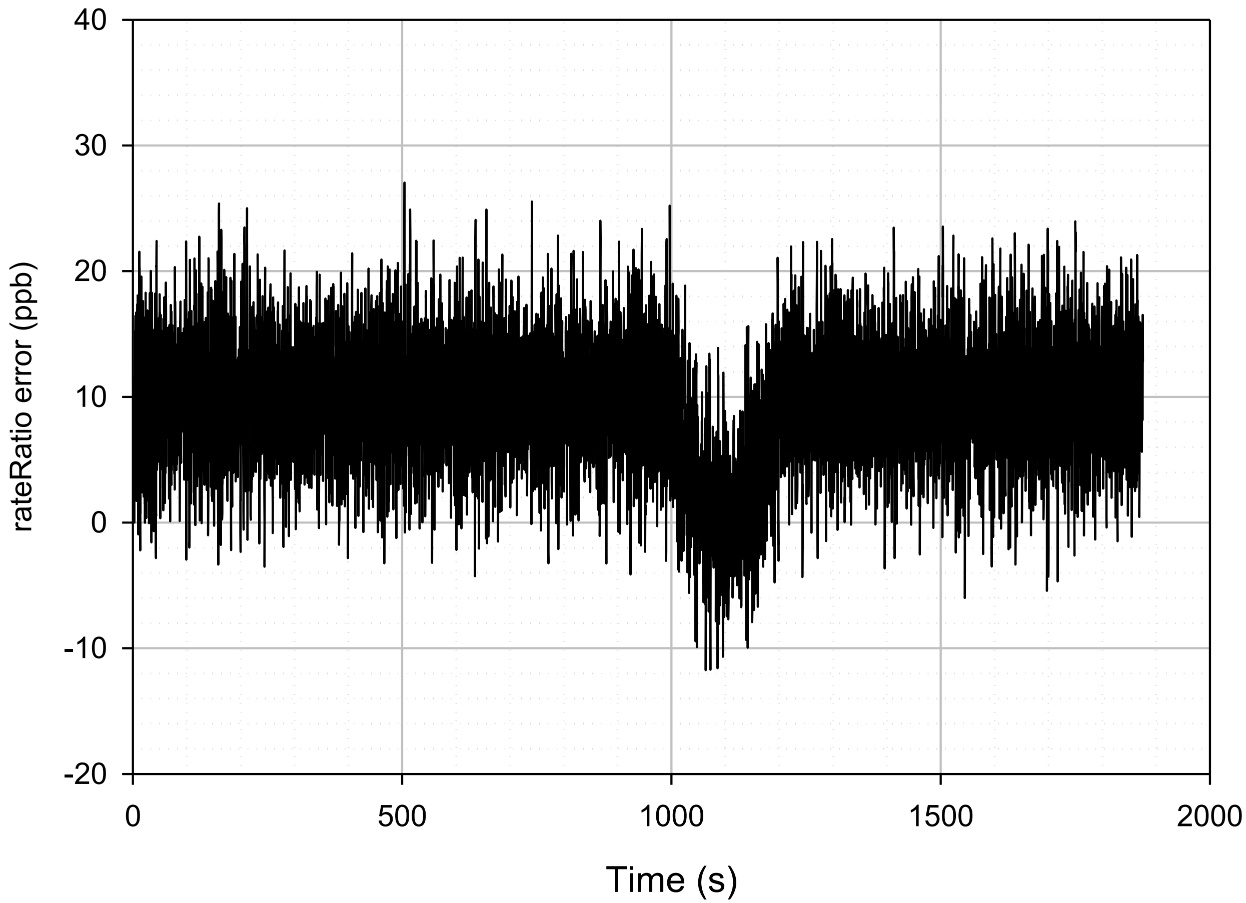


Plots for Case 4 – following 4 slides

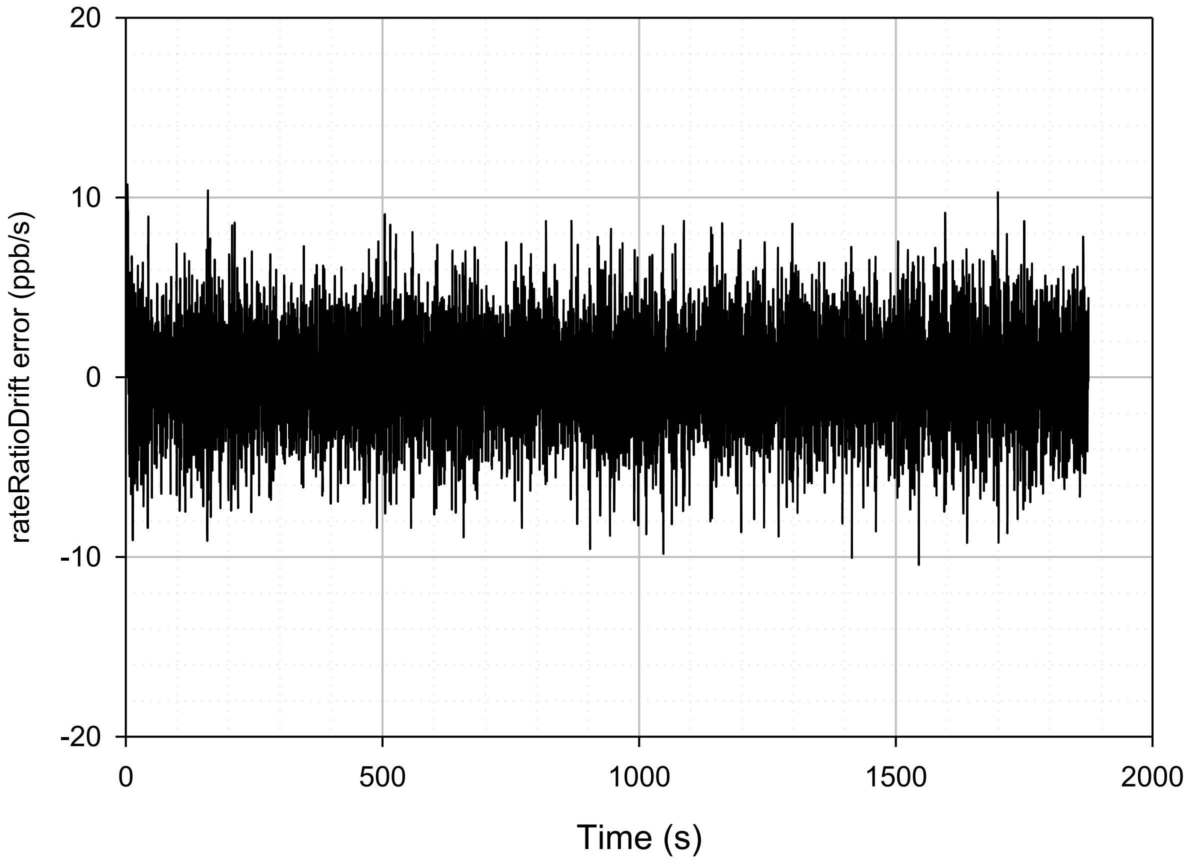
Case 4, Replication 1
preciseOriginTimestamp + correctionField - Working Clock at GM at transmission of Sync message
Full detail of initial transient not shown on scale of plot
Node 3



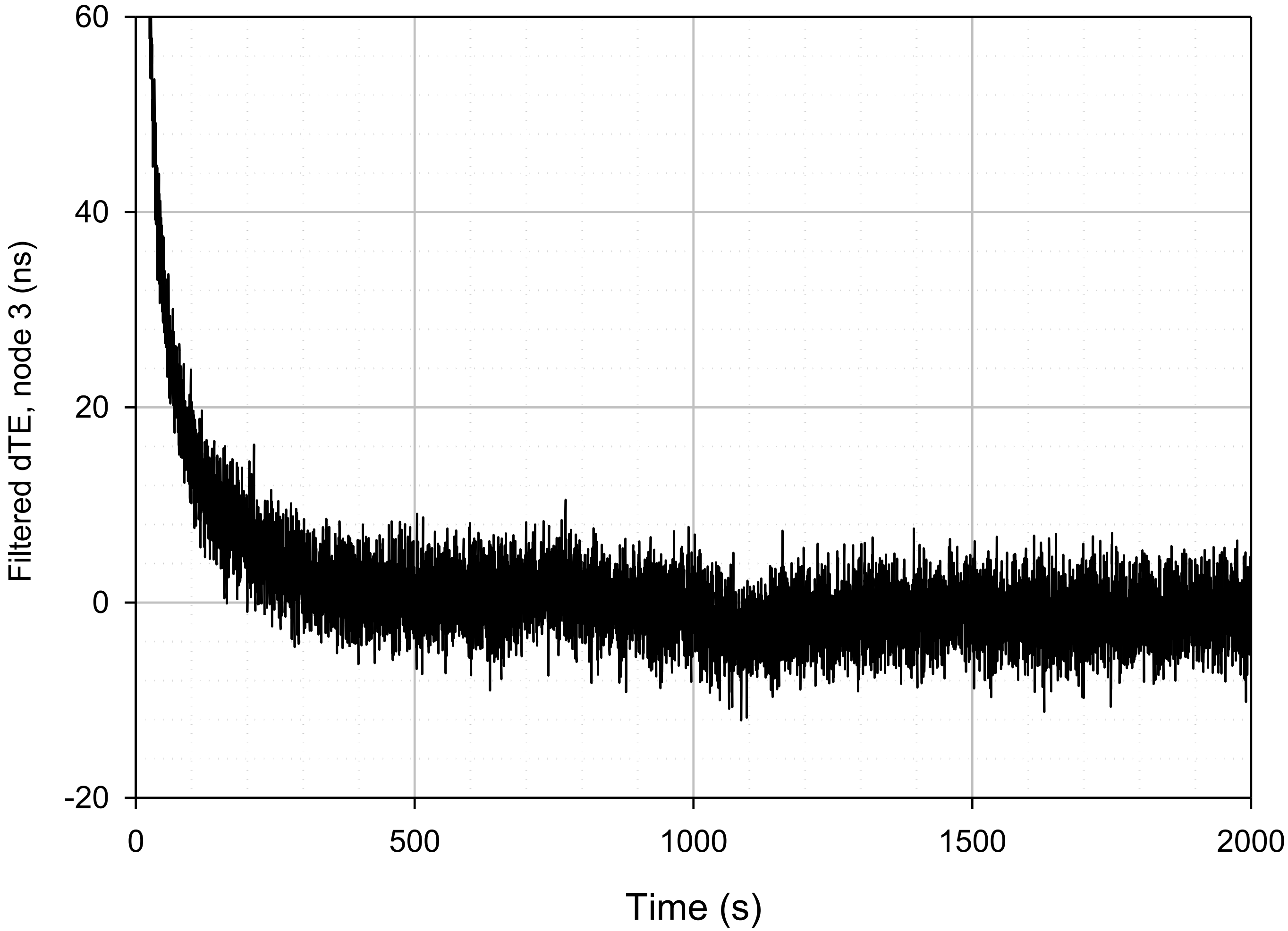
Case 4, Replication 1
rateRatio field of transmitted Sync message by DUT minus actual rate ratio of DUT working clock relative to Working Clock at GM at transmission of Sync message
Detail of initial transient not shown on scale of plot
Node 3



Case 4, Replication 1
rateRatioDrift field of transmitted Sync message by DUT minus actual rate ratio drift rate of DUT working clock relative to Working Clock at GM at transmission of Sync message
Detail of initial transient not shown on scale of plot
Node 3



Case 4, Replication 1
Filtered dTE (PTP End Instance), Node 3
Full detail of initial transient not shown on scale of plot



Experiment 2, 3, and 4 Results

Mean Link Delay (ns)						
	Case 2		Case 3		Case 4	
Statistic computed over time	**Minimum over 1000 replics**	**Maximum over 1000 replics**	**Minimum over 1000 replics**	**Maximum over 1000 replics**	**Minimum over 1000 replics**	**Maximum over 1000 replics**
Minimum over time	452.004	456.267	449.907	454.219	449.907	454.219
5th percentile over time	452.020	456.284	449.964	454.245	449.964	454.245
95th percentile over time	452.143	456.366	451.799	456.054	451.799	456.054
Maximum over time	452.161	456.383	451.966	456.254	451.966	456.254
Mean over time	452.184	456.319	450.703	454.947	450.703	454.947
Standard Deviation over time	0.011909	0.985173	0.019880	1.55113	0.019880	1.55113

Experiment 2, 3, and 4 Results - 2

preciseOriginTimeStamp+correctionField-(Working Clock at GM), when Sync is transmitted (i.e., M) (ns)						
	Case 2		Case 3		Case 4	
Statistic computed over time	**Minimum over 1000 replics**	**Maximum over 1000 replics**	**Minimum over 1000 replics**	**Maximum over 1000 replics**	**Minimum over 1000 replics**	**Maximum over 1000 replics**
Minimum over time	-13.694	-7.606	-15.706	-9.161	-15.664	-9.130
5th percentile over time	-9.352	-4.046	-10.609	-5.430	-10.592	-5.405
95th percentile over time	4.210	9.208	2.800	7.894	2.839	7.942
Maximum over time	7.870	13.688	6.713	13.326	6.746	13.392
Mean over time	-2.427	2.375	-3.778	1.028	-3.748	1.058
Standard Deviation over time	3.752	4.270	3.793	4.409	3.793	4.409

Experiment 2, 3, and 4 Results - 3

rateRatio field of Sync minus actual rate ratio, when Sync is sent (i.e., N) (ppb) [Red values are requirements from 60802 Table 13]						
	Case 2		Case 3		Case 4	
Statistic computed over time	**Minimum over 1000 replics**	**Maximum over 1000 replics**	**Minimum over 1000 replics**	**Maximum over 1000 replics**	**Minimum over 1000 replics**	**Maximum over 1000 replics**
Minimum over time	-26.370	-16.313	-26.370	-16.314	-17.880	-8.738
5th percentile over time	-13.698	-11.485	-13.698	-11.486	-6.429	-4.091
95th percentile over time	1.471	3.838	1.470	3.838	10.702	13.129
Maximum over time	54.818	86.876	54.817	86.877	15.416	27.105
Mean over time	-5.129 (±100 ppb)	-4.819 (±100 ppb)	-5.130 (±100 ppb)	-4.820 (±100 ppb)	3.128	3.222
Standard Deviation over time	4.439 (±80 ppb)	5.533 (±80 ppb)	4.439 (±80 ppb)	5.533 (±80 ppb)	4.767	5.698

Experiment 2, 3, and 4 Results - 4

rateRatioDrift field of Sync minus actual rate ratio drift, when Sync is sent (i.e., P) (ppb/s) [Red values are requirements from 60802 Table 13]						
	Case 2		Case 3		Case 4	
Statistic computed over time	**Minimum over 1000 replics**	**Maximum over 1000 replics**	**Minimum over 1000 replics**	**Maximum over 1000 replics**	**Minimum over 1000 replics**	**Maximum over 1000 replics**
Minimum over time	-12.732	-6.238	-12.732	-6.237	-12.705	-6.440
5^{th} percentile over time	-5.283	-3.699	-5.282	-3.699	-5.243	-3.710
95^{th} percentile over time	3.750	5.208	3.751	5.207	3.712	5.252
Maximum over time	592.847	1006.957	592.847	1006.958	6.215	12.955
Mean over time	0.3958 (±100 ppb/s)	1.071 (±100 ppb/s)	0.3958 (±100 ppb/s)	1.071 (±100 ppb/s)	-0.02841	0.03837
Standard Deviation over time	15.622 (±80 ppb/s)	30.152 (±80 ppb/s)	15.622 (±80 ppb/s)	30.152 (±80 ppb/s)	2.326	3.145

Experiment 2, 3, and 4 Results - 5

Filtered dTE (ns) [Red values are requirements from 60802 Table 14]						
	Case 2		Case 3		Case 4	
Statistic computed over time	**Minimum over 1000 replics**	**Maximum over 1000 replics**	**Minimum over 1000 replics**	**Maximum over 1000 replics**	**Minimum over 1000 replics**	**Maximum over 1000 replics**
Minimum over time	-115.200 (±17)	-107.410 (±17)	-116.880 (±17)	-108.940 (±17)	-14.205	-6.142
5^{th} percentile over time	-109.330 (±17)	-104.300 (±17)	-110.830 (±17)	-105.830 (±17)	-8.172	-3.126
95^{th} percentile over time	-100.610 (±17)	-95.760 (±17)	-101.870 (±17)	-96.940 (±17)	0.8829	5.766
Maximum over time	-97.510 (±17)	-89.330 (±17)	-98.610 (±17)	-90.260 (±17)	4.070	12.350
Mean over time	-104.737 (±17)	-100.271 (±17)	-106.111 (±17)	-101.576 (±17)	-3.416	1.118
Standard Deviation over time	2.449	2.966	2.468	3.187	2.477	3.169

Experiment 2, 3, and 4 Results - 6

- As in cases 1, 1b, and 1c, the actual mean link delay for the link between nodes 2 and 3 is 454.21 ns
- The requirement for the mean link delay error in Tables 13 and 14 of [1] is ± 3 ns
- This means that the measured mean link delay, after filtering, must be in the range [451.21, 457.21] ns
- However, not all the mean link delay results in the table on slide 83 are within this range
  - For case 2, the minimum is 452.004 ns and the maximum is 456.319 ns
  - For case 3, the minimum is 449.907 ns and the maximum is 454.947 ns
  - For case 4, the minimum is 449.907 ns and the maximum is 454.947 ns
  - The ranges for 3 and 4 are almost the same
  - The mean link delay requirement is met for case 2, but not for cases 3 and 4
    - Cases 3 and 4 both have clock drift at node 2, while for case 2 the clock drift at node 2 is zero

Experiments 2, 3, and 4 Results - 7

- For M, N, P, and filtered dTE, the requirements of Tables 13 and 14 of [1] are shown in red in the results tables on slides 114 (for N), 115 (for P), and 116 (for filtered dTE)
  - Note that there are no requirements on M in Tables 13 and 14 for cases with clock drift (cases 2, 3, and 4)
  - Also note that no requirements are shown for case 4, because case 4 is not included in Tables 13 and 14
    - Case 4 is included here as a possible replacement for cases 2 and 3 that can meet the filtered dTE requirements (they are not met for cases 2 and 3, see below)
- The requirements are only shown for applicable quantities of Tables 13 and 14, even though other quantities also meet the requirements
- All requirements of Tables 13 and 14 for N and P are met
  - Note that all the outputs (mean link delay, M, N, P, Filtered dTE) are computed only between 1005 s and 1200 s, i.e., the transients due to starting and stopping the clock drift are not included

Experiments 2, 3, and 4 Results - 8

- The results for N, P, and filtered dTE show transients when the clock drift starts and stops, for cases 2 and 3 (but not for case 4)
  - This is due the replicas GM clock drift, which is not present in case 4
- The results for N show a decrease (i.e., an overall downward shift in the time history) during the period of clock drift, for cases 2, 3, and 4 (see plots on slides 94, 102, and 111)
- The results for N and P are very similar for cases 2 and 3, respectively, which are not similar to case 4 (see plots on slides 94, 96, 102, 104, 109, and 110)
  - This indicates that N and P are influenced more by clock drift at the GM rather than at node 2 (because both cases 2 and 3 have GM clock drift, but case 4 has only node 2 clock drift)

Experiments 2, 3, and 4 Results - 9

- For filtered dTE, the requirements of Table 14 are not met for cases 2 and 3
- As in [8], cases 2 and 3 exhibit a steady-state offset during the clock drift of approximately 100 – 110 ns (see plots on slides 89, 90, 97, and 98)
- This offset is due to the inability of a 2nd – order filter with 20 dB/decade rolloff to follow a frequency drift with zero steady state error
- The frequency drift that node 3 attempts to follow is the GM frequency drift, which is present in both cases 2 and 3
- The proof of this was shown in [8]; for convenience, it is reproduced on the next slide
- Note that while drift tracking and compensation algorithms at the PTP End Instance are included in the simulations here (and were not included in the simulations of [8]), the GM drift still cannot be followed with zero steady-state error because the effect of the filter is to slow down the use of incoming information from upstream (i.e., the information is used on a timescale of the order of the filter time constant
  - In the proof on the next slide, the input frequency is “perfect” and still cannot be followed

Experiments 2, 3, and 4 Results - 9

- The -100 ns phase offset is due to the response of the second-order filter to the 1 ppm/s frequency drift
- To see this, note that the phase drift corresponding to an $A = 1$ ppm/s $= 1000$ ns/s frequency drift is $0.5At^2$, where t is the time in seconds
  - The Laplace transform of this waveform is $U(s) = A/s^3$
  - The steady-state value of the filter output due to this drift is obtained from the final value theorem:

$$\text{steady-state-response} = \lim_{s\to 0} sH(s)U(s) = \lim_{s\to 0} s \cdot \frac{s^2}{s^2 + 2\varsigma\omega_n s + \omega_n^2} \cdot \frac{A}{s^3} = \frac{A}{\omega_n^2}$$

where

$\omega_n = \text{undamped natural frequency} = 3.1011 \text{ rad/s}$

$\varsigma = \text{ damping ratio } = \text{ } 2.1985 \text{ dB}$

  - Then the steady-state response is

$$\frac{A}{\omega_n^2} = \frac{1000 \text{ ns/s}}{(3.1011 \text{ rad/s})^2} = 104 \text{ ns}$$

  - This is in agreement with the steady-state filtered dTE during the 1 ppm/s clock drift for cases 2 and 2N

Experiments 2, 3, and 4 Results - 10

- The above means that a test with non-zero GM clock drift is not an appropriate test, because under the assumptions of the test it is mathematically impossible to pass
- One solution to this is to change the test to not have GM clock drift
- Case 4 is introduced as a possible test that could replace cases 2 and 3 for the filtered dTE test of Table 14 (note: tests 2 and 3 can remain for mean link delay, M, N, and P)
- In case 4, there is clock drift at node 2 but ***not*** at the GM
- The results for filtered dTE on slide 116 indicate that the $\pm$17 ns requirement for filtered dTE in Table 14 is met for case 4
  - The plot on slide 116 for case 4 filtered dTE shows no transients and no jump during the 1005 – 1200 s period

Conclusions - 1

- All the requirements of IEC/IEEE 60802 [1], Tables 13 and 14 are met, except for the following:
  - For cases with clock drift at node 2 (cases 3 and 4), the measured mean link delay error is in the range [-4.3, 0.74] ns instead of ±3 ns
  - For cases with clock drift at the GM (cases 2 and 3), the filtered dTE has an approximately -104 ns phase step due to the inability of the second-order filter (with 20 dB/decade rolloff) to follow the clock drift with zero steady-state error
    - This exceeds the Table 14 requirement of [-17, +17] ns for the range of filtered dTE
    - However, the filtered dTE is in the range [-14.205, +12.350] ns for case 4, which meets the requirement

Conclusions - 2

- As pointed out on slides 18 and 19, all the simulations assumed zero noise generation for the endpoint filter; in addition, the local oscillator of the DUT was assumed to be stable. This implies that, at the very least, the tests are done at constant temperature. The following statement related to this is repeated in the paragraphs just before Table 13 and Table 14 (in 6.2.5 of [1]), respectively (in this paragraph, "its Local Clock refers to the Local Clock of the DUT):
  - These requirements are written for the case when errors due to change of fractional frequency offset of its Local Clock with respect to the nominal frequency and errors in the input Sync message are negligible with respect to the specified error generation limits.
- The above statement should be sufficient to make it clear that the tests need to be done in an environment that does not cause additional clock drift of the DUT Local Clock (e.g., the tests should be done at constant temperature). However, if it is felt that this is not sufficiently clear, a statement on this should be added, either to 6.2.5 or Annex D of [1].

Recommendations

- Based on the first Conclusions slide:
  - In Table 14 of [1], delete row 2 after the header
  - In Table 14 of [1], replace the first bullet item of row 3 after the header by "Working Clock (acting as ClockSource) at Grandmaster is stable
  - Assuming meanLinkDelay error is measured in all the cases (i.e., with no clock drift and with clock drift at the various nodes as specified in Tables 13 and 14), change the requirement on measured meanLinkDelay error to account for the exceedance of ± 3 ns when there is clock drift at node 2
    - The revised requirement must accommodate a range of [-4.3, +0.74] ns for cases with clock drift at node 2
    - A limit of ± 4.5 ns or ± 5 ns would accomplish this

Thank you

References - 1

[1] IEC/IEEE 60802 Time-Sensitive Networking Profile for Industrial Automation, Draft 2.2, February 2024.

[2] David McCall, *IEC/IEEE 802 Contribution – Annex D (Informative), Time Synchronization Informative Annex, Version 9*, October 2023 (available at https://www.ieee802.org/1/files/public/docs2023/60802-McCall-Time-Sync-Informative-Annex-Clean-1023-v09.pdf)

[3] David McCall, *60802 Time Sync – Error Generation Normative Requirements & Next Steps, Version 2*, IEC/IEEE 60802 presentation, June 2023, (available at https://www.ieee802.org/1/files/public/docs2023/60802-McCall-Error-Generation-Normative-Requirements-1123-v02.pdf).

[4] Geoffrey M. Garner, *New Multiple Replication 60802 Time Domain Simulation Results for Cases with Drift Tracking Algorithms and PLL Noise Generation*, Revision 1, October 20, 2023 (available at https://www.ieee802.org/1/files/public/docs2023/60802-garner-new-time-domain-simul-results-with-drift-tracking-algorithms-and-PLL-noise-generation-multiple-replic-1023-v01.pdf)

References - 2

[5] ITU-T Rec. G.8251, *The control of jitter and wander within the optical transport network*, ITU-T, Geneva, November 2022

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

[7] John Rogers, Calvin Plett, Foster Dai, *Integrated Circuit Design for High-Speed Frequency Synthesis*, Artech House, 2006

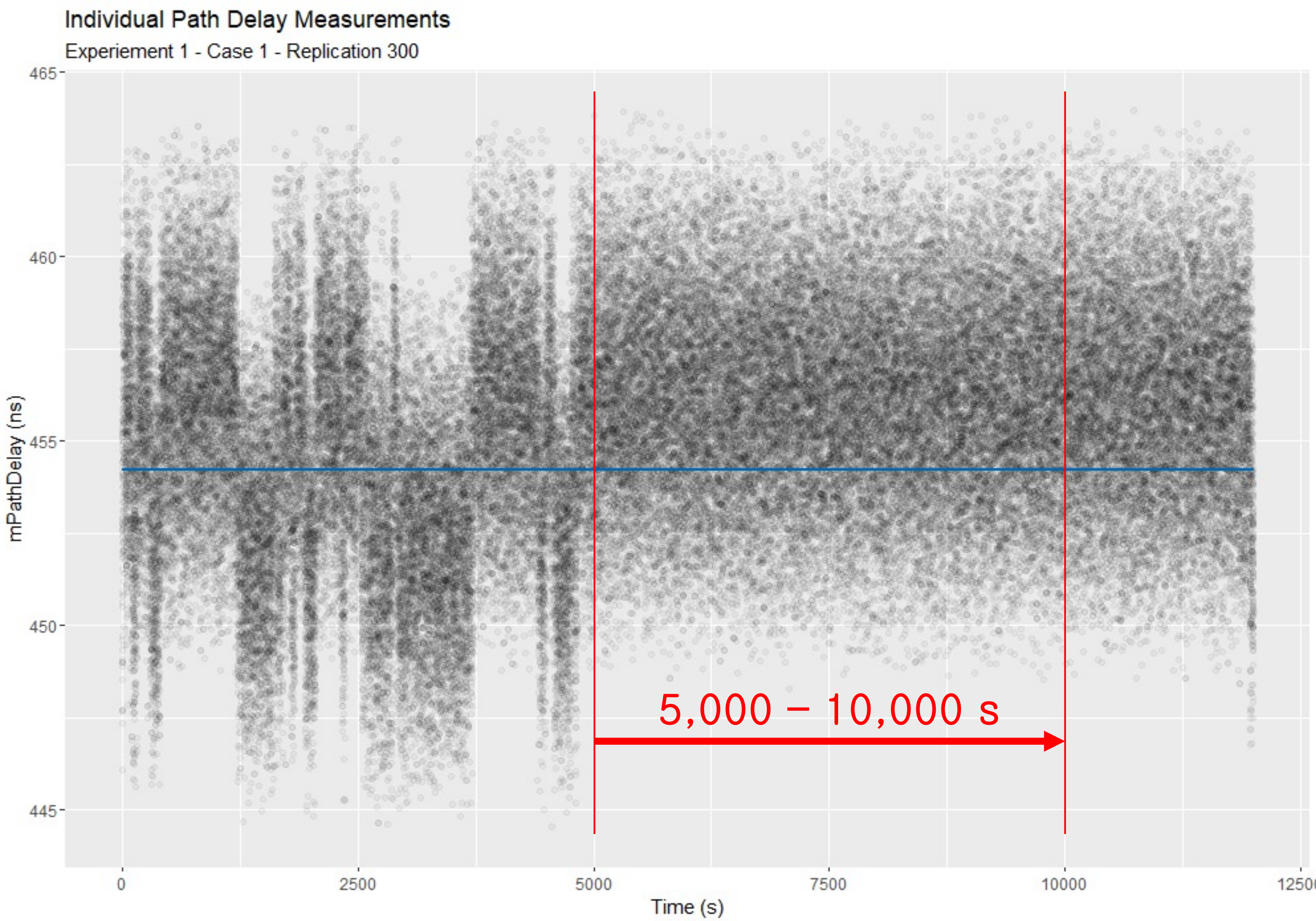
[8] Geoffrey M. Garner, Initial *60802 Error Generation Time Series Simulation Results, Version 1*, January 22, 2024 (available at https://www.ieee802.org/1/files/public/docs2024/60802-garner-error-generation-time-series-simulation-results--0124-v01.pdf)

[9] David McCall, Geoff Garner, Silvana Rodrigues, *60802 Time Sync – Error Generation Simulations Time Series Assumptions, Version 2*, January 25, 2024 (available at https://www.ieee802.org/1/files/public/docs2024/60802-McCall-Garner-Rodrigues-Error-Generation-Simulations-Assumptions-0124-v02.pdf)

[10] David McCall, Figure supplied on February 24,2024

Distribution of mPathDelay Measurements

- Looking at a stable section of a plot…

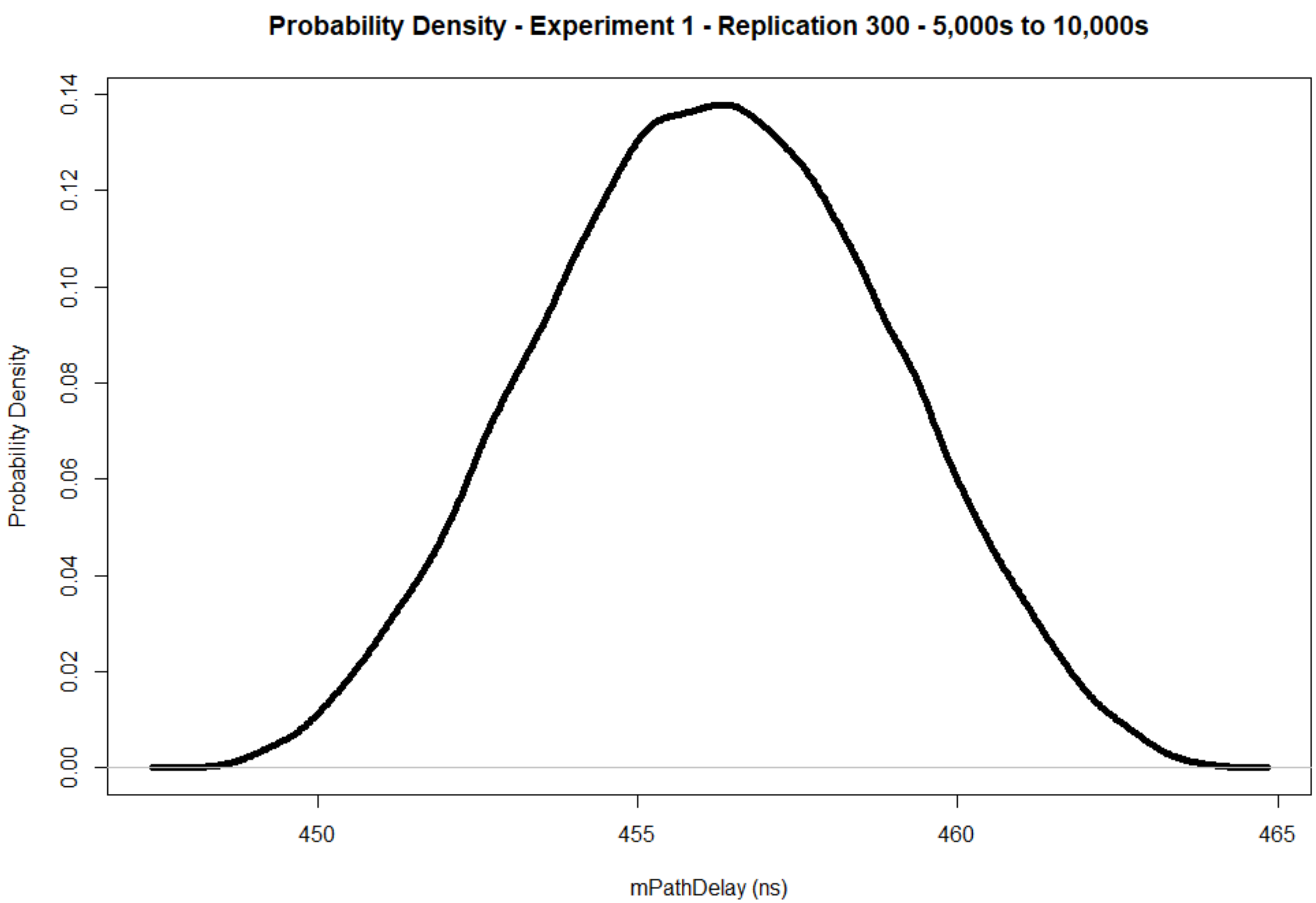


Backup

- The following backup slides were supplied by David McCall, March 2024

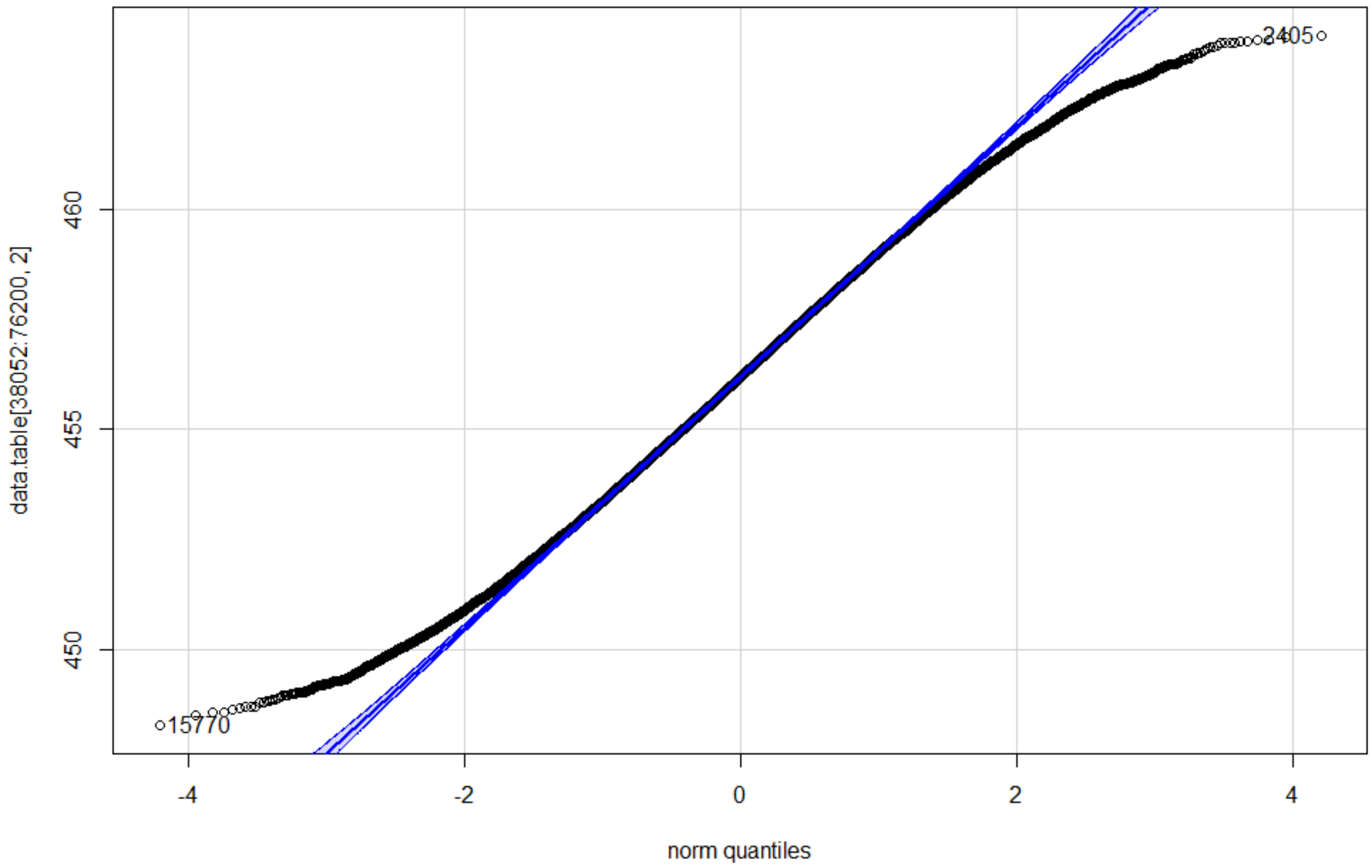
Distribution of mPathDelay Measurements

- Density distribution looks similar to a normal distribution…



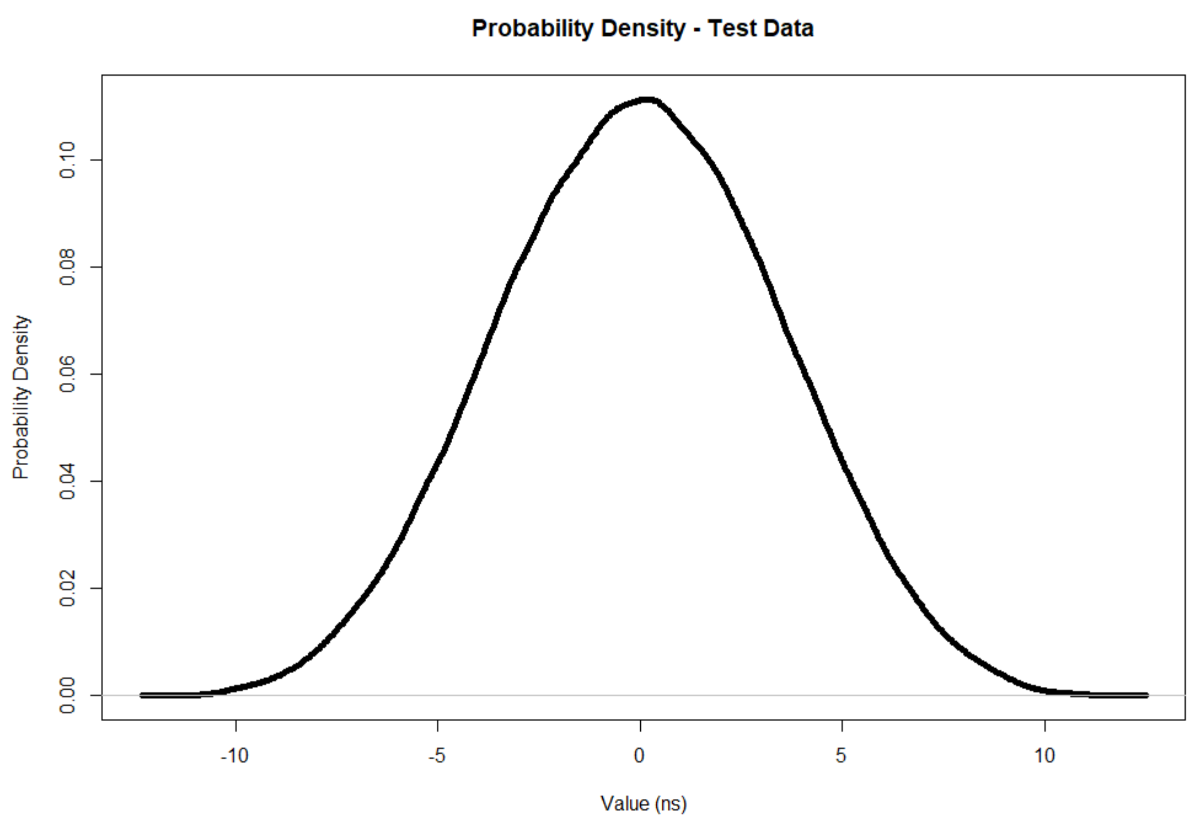
Distribution of mPathDelay Measurements

- QQ Plot shows that it is NOT a normal distribution…



Distribution of mPathDelay Measurements

- Repeatedly stacking 4 DTSE values on top of each other yields similar results
  - R Studio script generates 100,000 samples, each of the sum of 4 x DTSE values (divided by 2).



Distribution of mPathDelay Measurements

- QQ Plot is also similar…