Revised 60802 Error Generation Time Series Simulation Results
Version 0

Geoffrey M. Garner
Analog Devices (Consultant)

gmgarner@alum.mit.edu

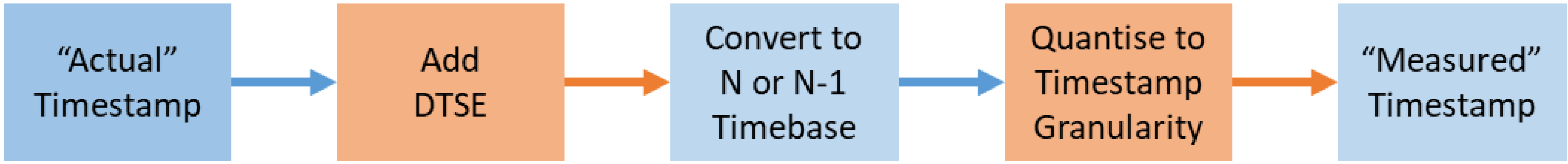
IEEE 802.1 TSN TG
2024.04.26

New Introduction (Preface)

- This presentation contains a major revision of the assumptions and results for the error generation simulation results of [11]
- While the presentation can be considered a revision of [11], there is a large amount of new or revised content
  - As a result, it is considered a new presentation
  - However, most of the background material is taken from [11]
- The next slide summarizes the new or revised assumptions, compared to the assumptions of [11]
- The remainder of the presentation follows [11]
  - Much of the material is copied from [11], with revisions where needed; this includes the revised assumptions and the new simulation results
  - In some cases, the revisions are shown in green so they can be easily found by the reader (green is chosen rather than red because red is already used in some slides to emphasize some points)

Revised Assumptions Relative to [11] - 1

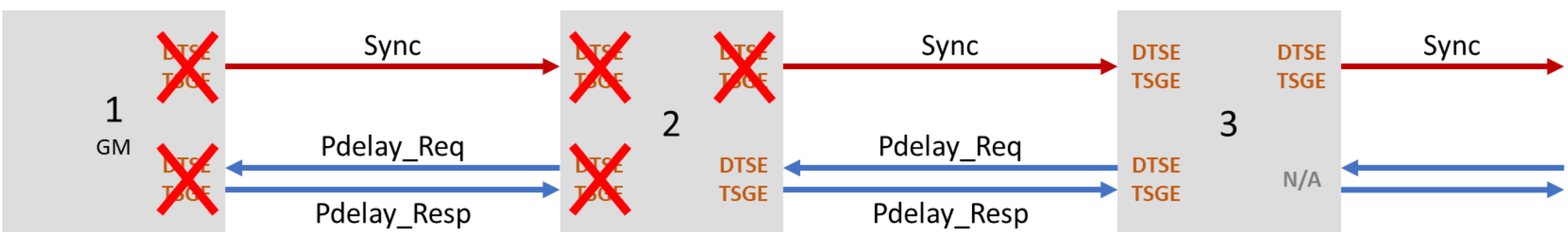
- The Pdelay interval is assumed uniformly distributed in the range [119 ms, 131 ms] (same as Sync Interval)
- Dynamic timestamp error is added before computing the effect of timestamp granularity, rather than after (see figure below, supplied by [12]



- For Sync messages, dynamic timestamp error (DTSE) and timestamp granularity error (TSGE) are set to zero at all ports of nodes 1 and 2, but are nonzero at node 3 (device under test (DUT)) or node 4 (irrelevant at node 4)
- For Pdelay messages, DTSE and TSGE are set to zero for (see figure on next slide, supplied by [12])
  - Receipt of Pdelay_Req and sending of Pdelay_Resp at node 1
  - Sending of Pdelay_Req from node 2 to node 1 and receipt of Pdelay_Resp at node 2 from node 1

Revised Assumptions Relative to [11] - 2

- For Pdelay messages, DTSE and TSGE are nonzero for
  - Receipt of Pdelay_Req at node 2 from node 3 and sending of Pdelay_Resp from node 2 to node 3
  - Sending of Pdelay_Req from node 3 to node 2 and receipt of Pdelay_Resp at node 3 from node 2
  - Sending and receiving of all Pdelay messages at node 4 (irrelevant at node 4)
  - See figure below, supplied by [12]



  - Note: Contrary to the above, DTSE is actually zero for receipt of Pdelay_Req and sending of Pdelay_Resp between nodes 2 and 3. However, this should not have appreciable impact on the results; see the Appendix

Revised Assumptions Relative to [11] - 3

- When computing TSGE, ½ of the timestamp granularity is added after the truncation for all timestamps at all nodes, rather than only at the GM, as was previously done
  - This is because, given the above assumptions, TSGE is set to zero for some messages at some ports but not at other ports
  - As a result, the ½ of timestamp granularity at successive nodes (other than the GM) does not cancel, as it does for the full system-level HRMs
- When computing the effect of random variation in Sync interval, Pdelay interval, residence time, and pdelay turnaround time, the random variation is assumed to be relative to the ideal simulator clock rather than the local clock
  - Previously, these random variations were assumed to be relative to the local clock, and an approximate model was used to convert them to the ideal clock timebase (see 11.2.1 of [6] for description of this model)
  - The effect of TSGE caused the jumps that were seen in computed unfiltered mean path delay; with this revised assumption, the jumps are eliminated

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 of [3]) meet the requirements of Table 12 of [1]

Introduction - 2

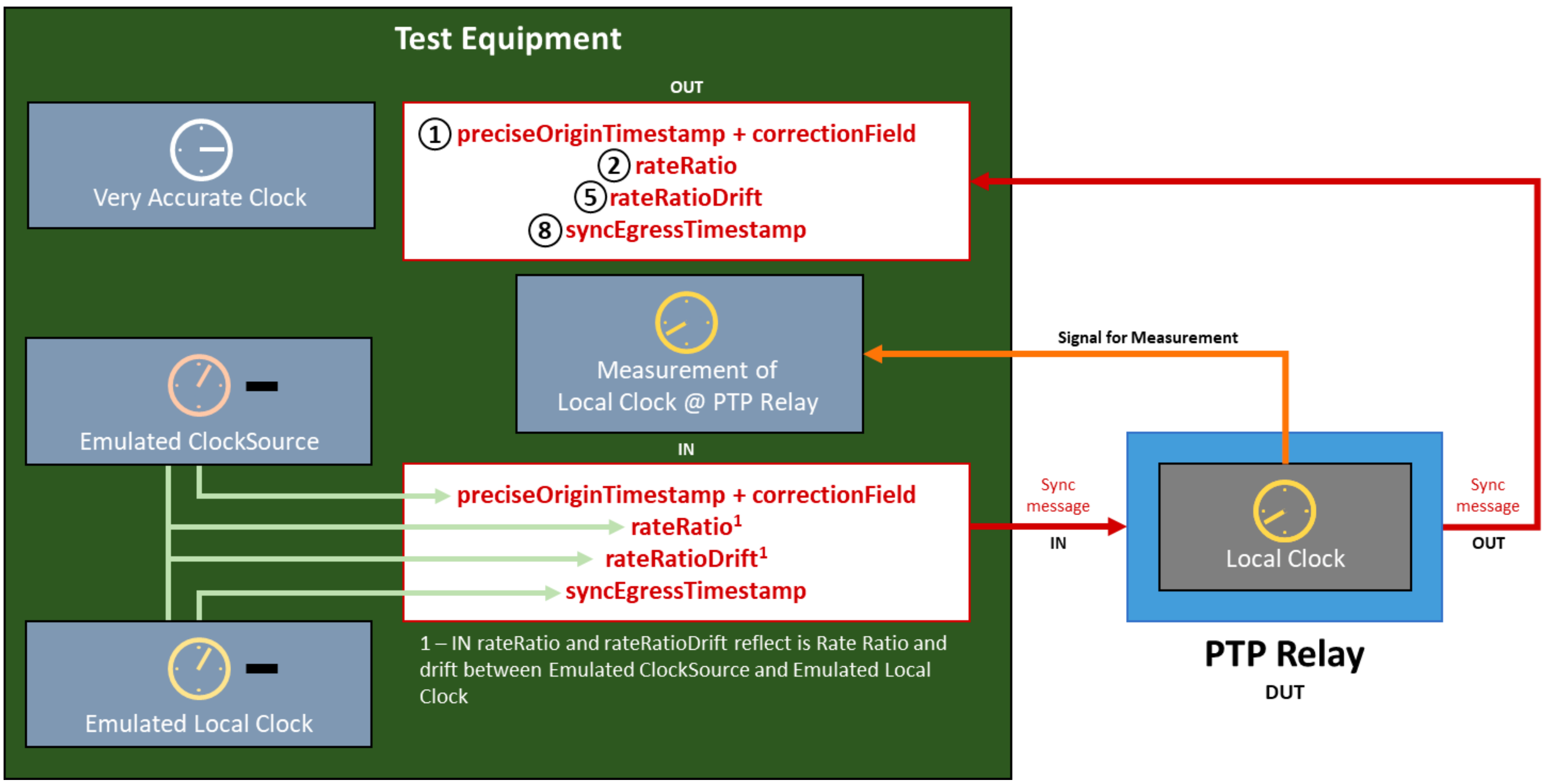
- One of the next steps described in [3] is to run time series simulations for the test cases of Annex D of [1], for both PTP Relay Instances and PTP End Instances
  - Time series simulations are needed for PTP End instances in particular because dTE results End Instances are after any endpoint filtering
- 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 (the statistics are described later and based on [9])

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

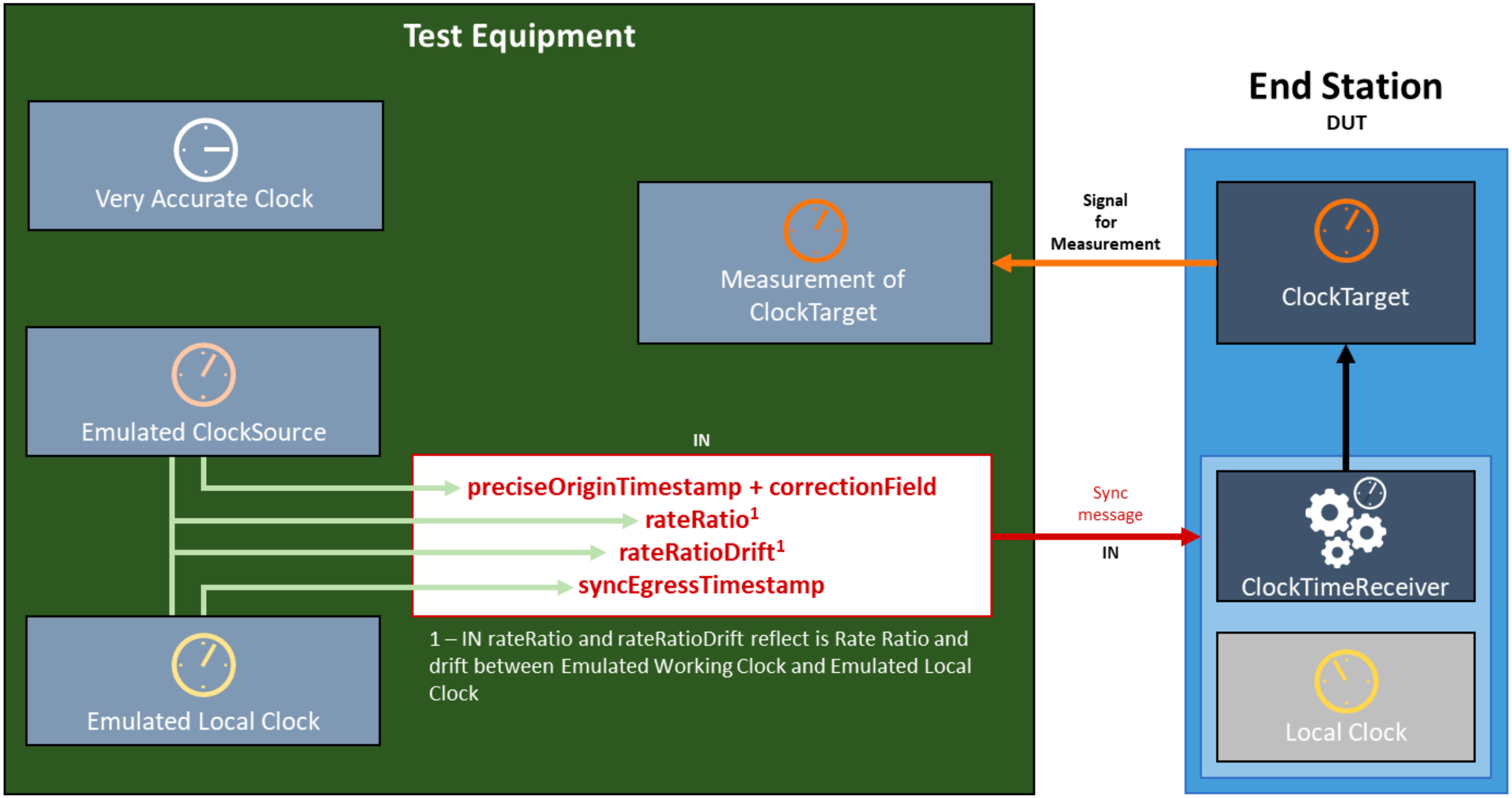
Description of Test Setup and Model for Simulator - 2

- 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

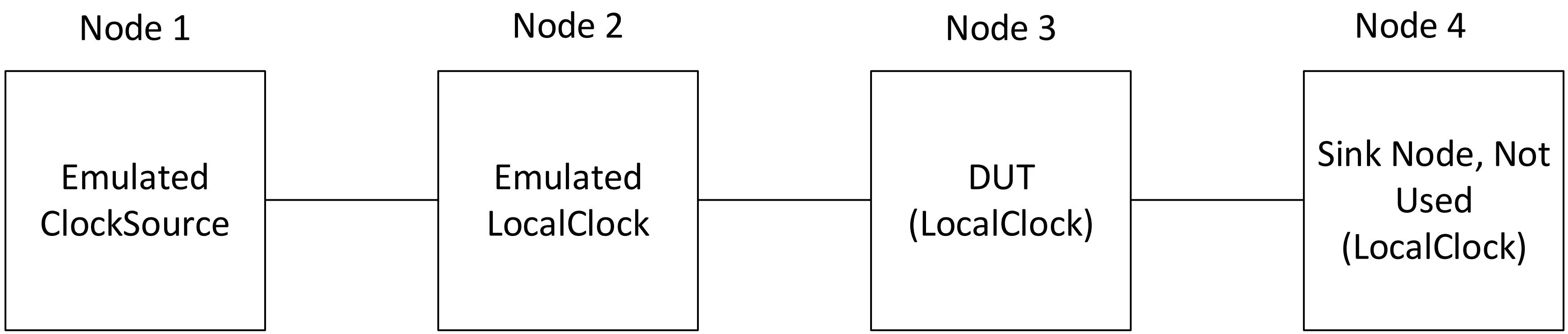


Description of Test Setup and Model for Simulator - 4

- 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 revised assumptions on slides 1 – 3 either modify or add to the assumptions on this and the next 7 slides
- 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, where present, 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 [119 ms, 131 ms] ~~[(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

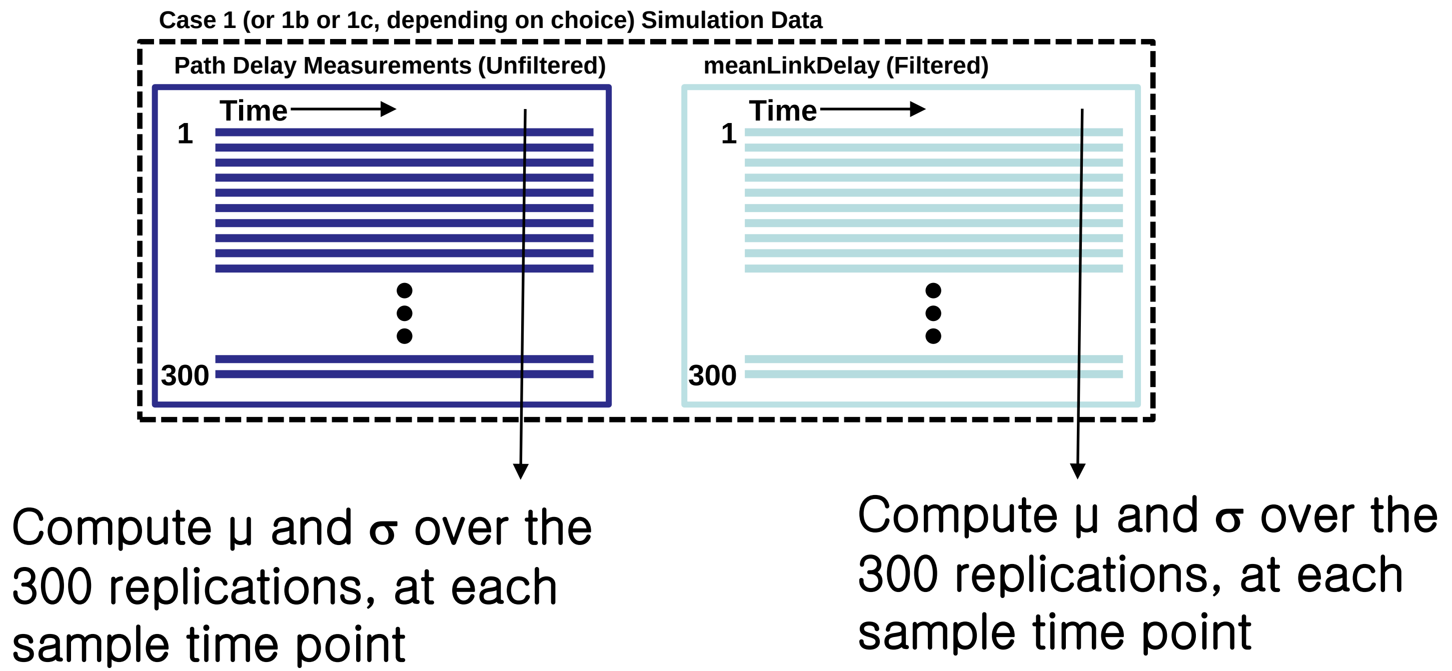
Clock offset and drift in cases 2, 3, and 4 is as described above in Assumptions slide 7

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])



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 path delay before IIR filtering – replication 1
  - Mean path 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

- All the Experiment 1 time history results show only the first 10,000 seconds of simulation time, rather than the full 100,000 s
  - This is because the full 100,000 s would result in very large plot files and very slow response in viewing the presentation ppt or pdf file)
- While time history plots of simulation results in previous presentations have had successive data points connected by straight lines, this is not done for the link delay results here because the unfiltered results are quantized due to the 8 ns timestamp granularity
  - The quantization is 4 ns (i.e., one-half the granularity)
- The effect is seen in the plots on slides 37 and 38 (replications 1 and 300, respectively)
  - If successive points were connected, the plot would appear as a “solid block” taking on all values in the range of mean link delay
- The peak-to-peak range of unfiltered mean path delay is 16 ns (this is twice the 8 ns timestamp granularity; the ±6 ns DTSE at node 3 is not sufficient to result in additional levels

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

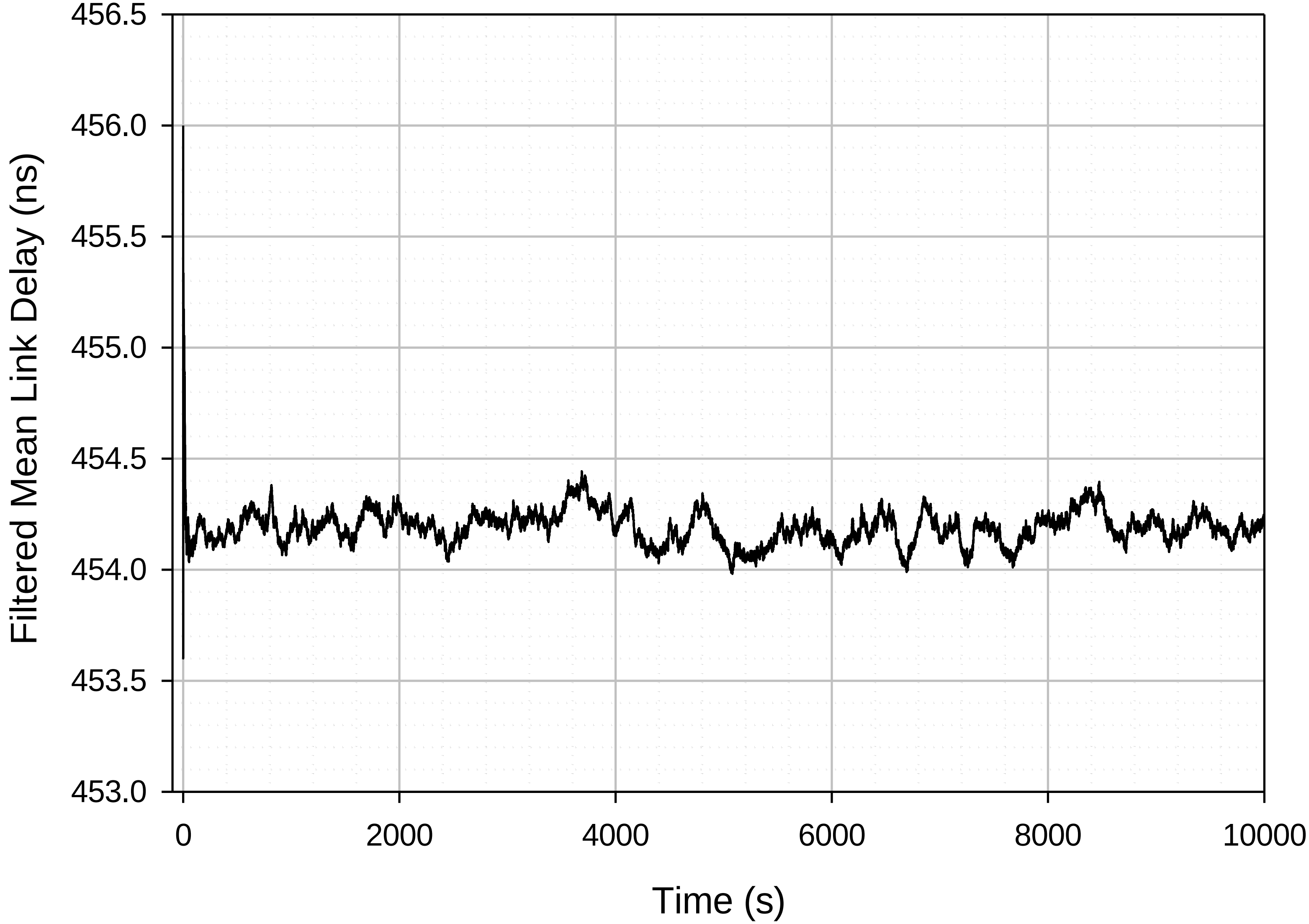
- There is additional randomness due to the nonzero pdelay turnaround time at node 2
- The averaging filter results in measured filtered mean link delay that varies about the actual mean link delay of 454.21 ns for the individual replications
- The mean link delay averaging uses a window of 1000 peer delay exchanges (after the startup behavior, which is different; see Assumptions slide 5)
  - The Pdelay interval varies uniformly from 119 ms to 131 ms; the mean of this distribution is125 ms, which means that 1000 exchanges would occur over an interval of 1250 s on average
  - This means that the time constant of the averaging filter is on the order of hundreds of seconds
  - All the variation in the measurements is fast variation, which is removed by the averaging filter

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

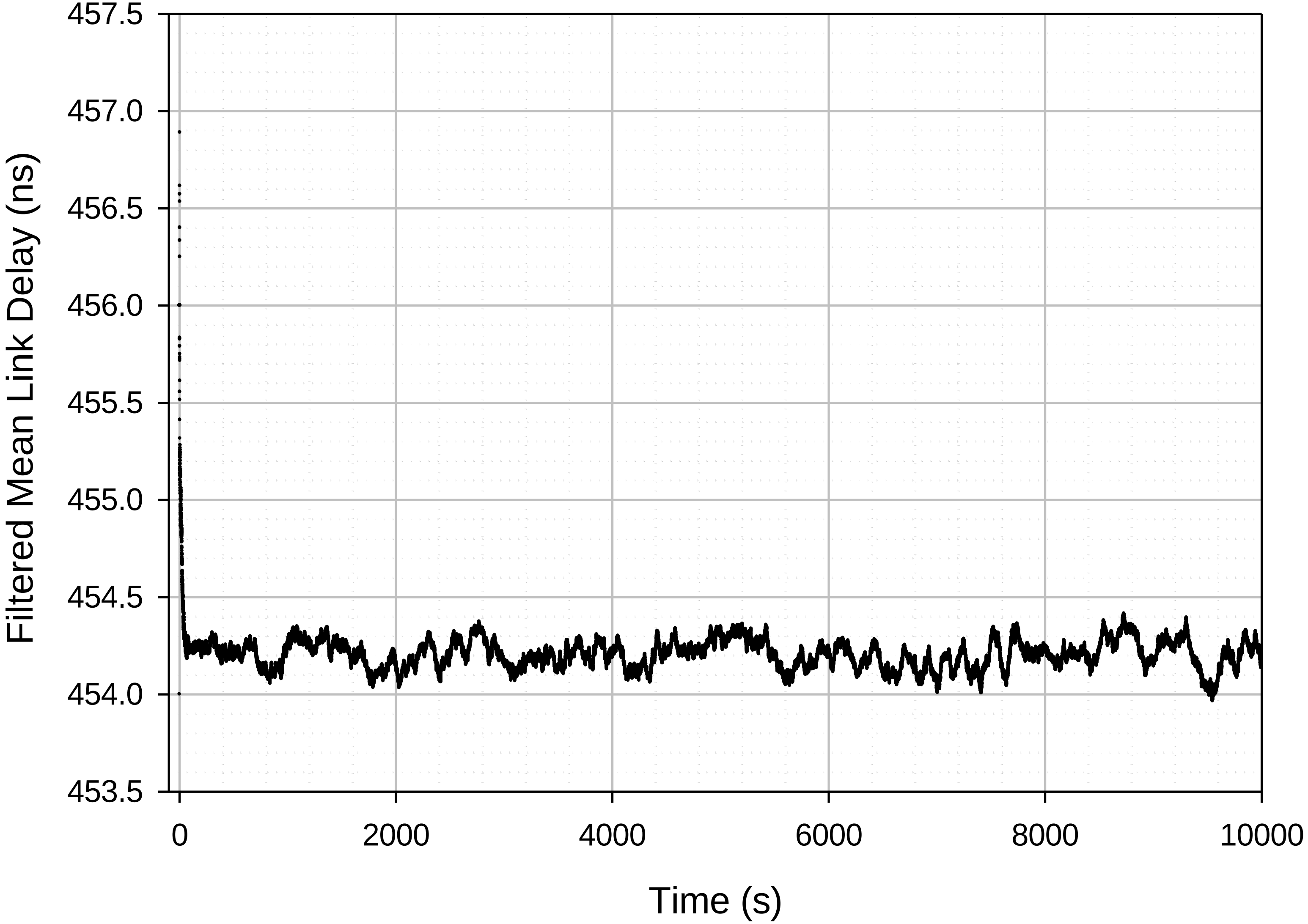
- The measured filtered mean link delays for cases 1, 1b, and 1c are qualitatively very similar (i.e., the filtered time histories for all three cases show the same behavior described in the previous slides)
- The unfiltered mean path delays for cases 1b and 1c show the levels “smeared out” (i.e., more variability) due to the clock drift present in these cases
  - This is consistent with results shown in [13]
- The mean of the filtered mean link delay, averaged over the 300 replications, is very similar for cases 1 and 1b, and somewhat more variability for case 1c
- The mean of the unfiltered mean measured mean path delay, averaged over the 300 replications, is also very similar for cases 1 and 1b, shows shows somewhat more variability for case 1c
- The standard deviation of the unfiltered mean path delay and filtered mean link delay, averaged over the 300 replications, is similar for cases 1, 1b, and 1c

Results for Case 1 – following 10 slides

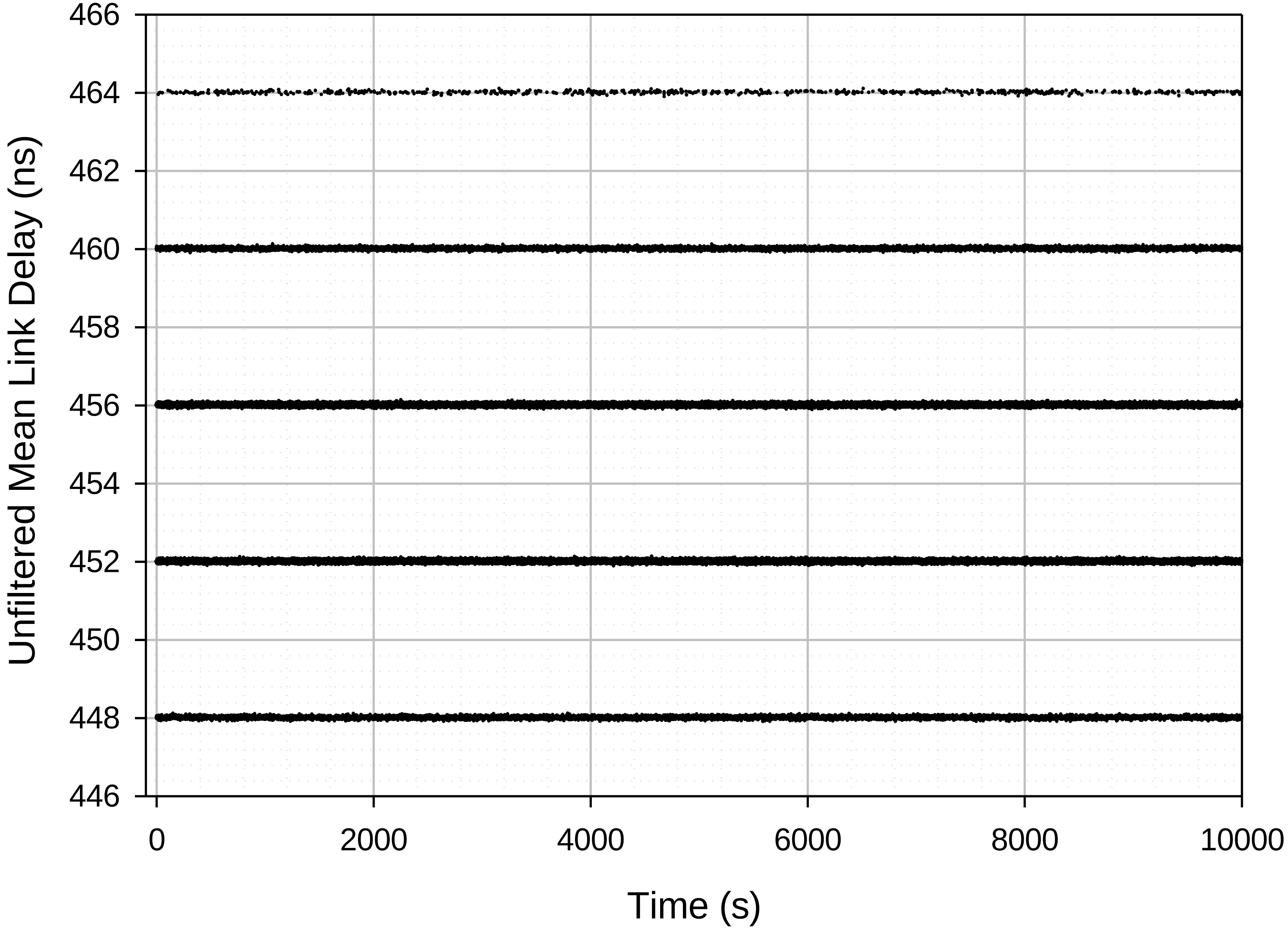
Case01 - Mean Link Delay after IIR Filtering - Replication 1



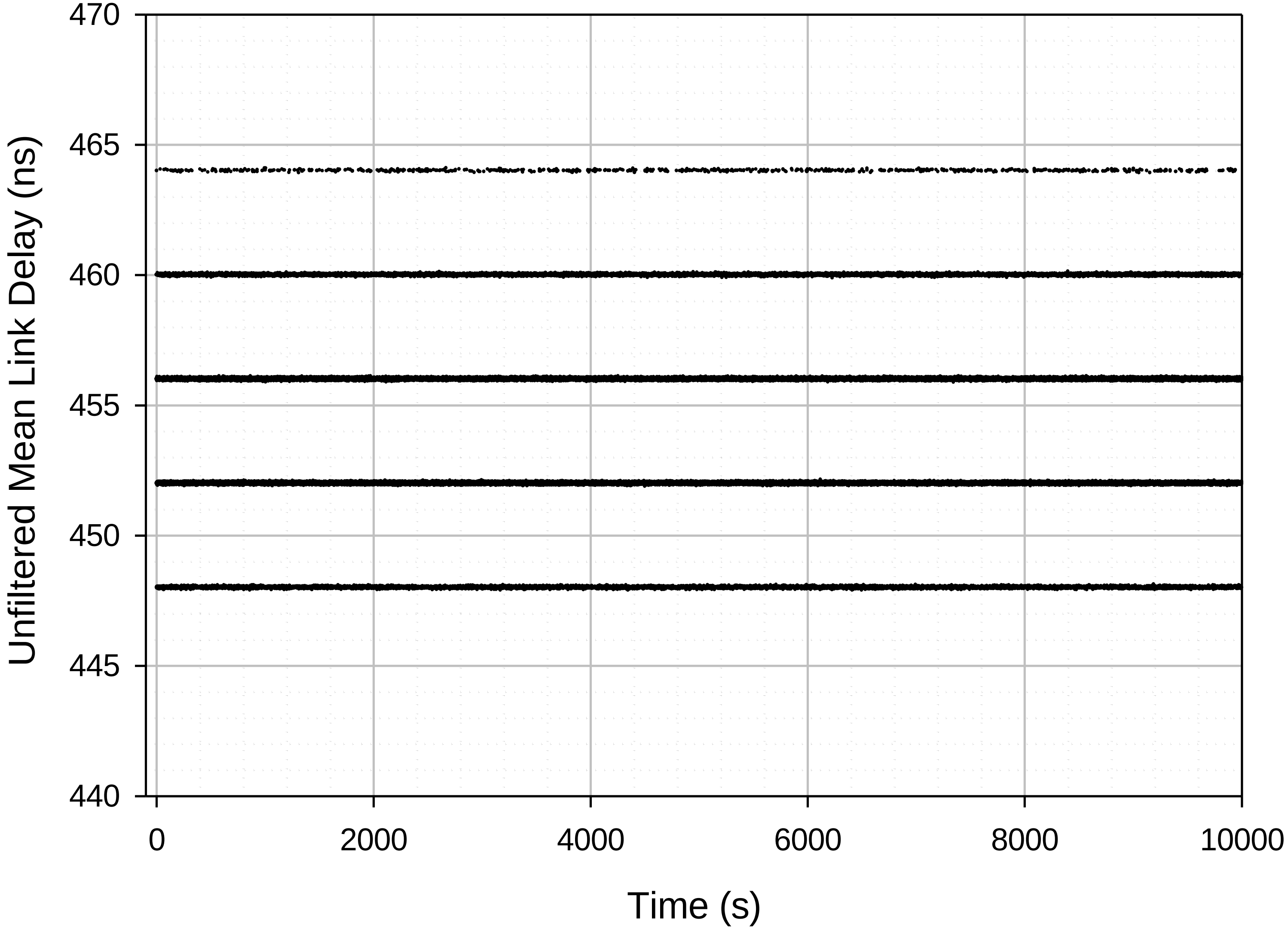
Case01 - Mean Link Delay after IIR Filtering - Replication 300



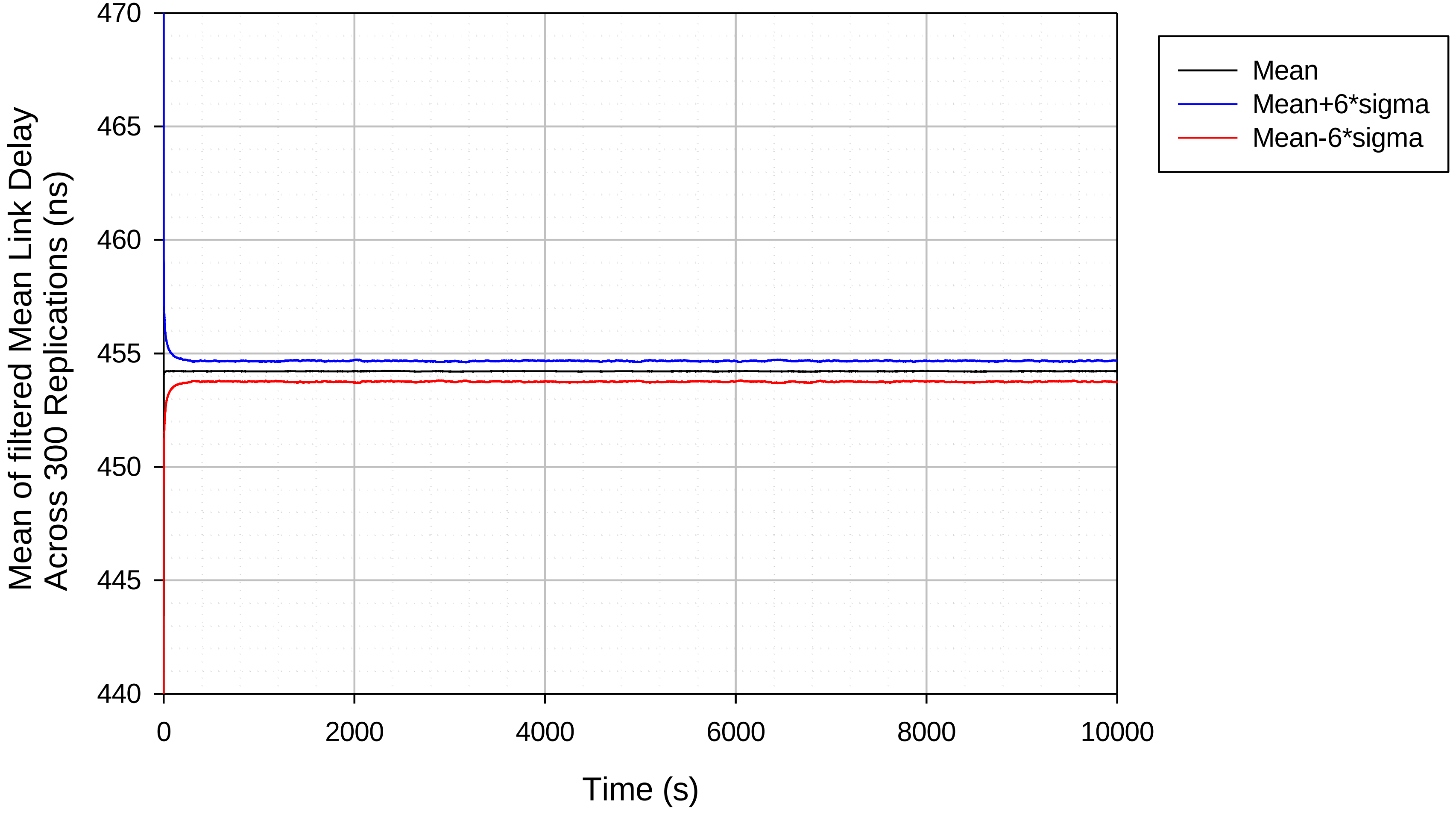
Case01 - Mean Link Delay before IIR Filtering - Replication 1



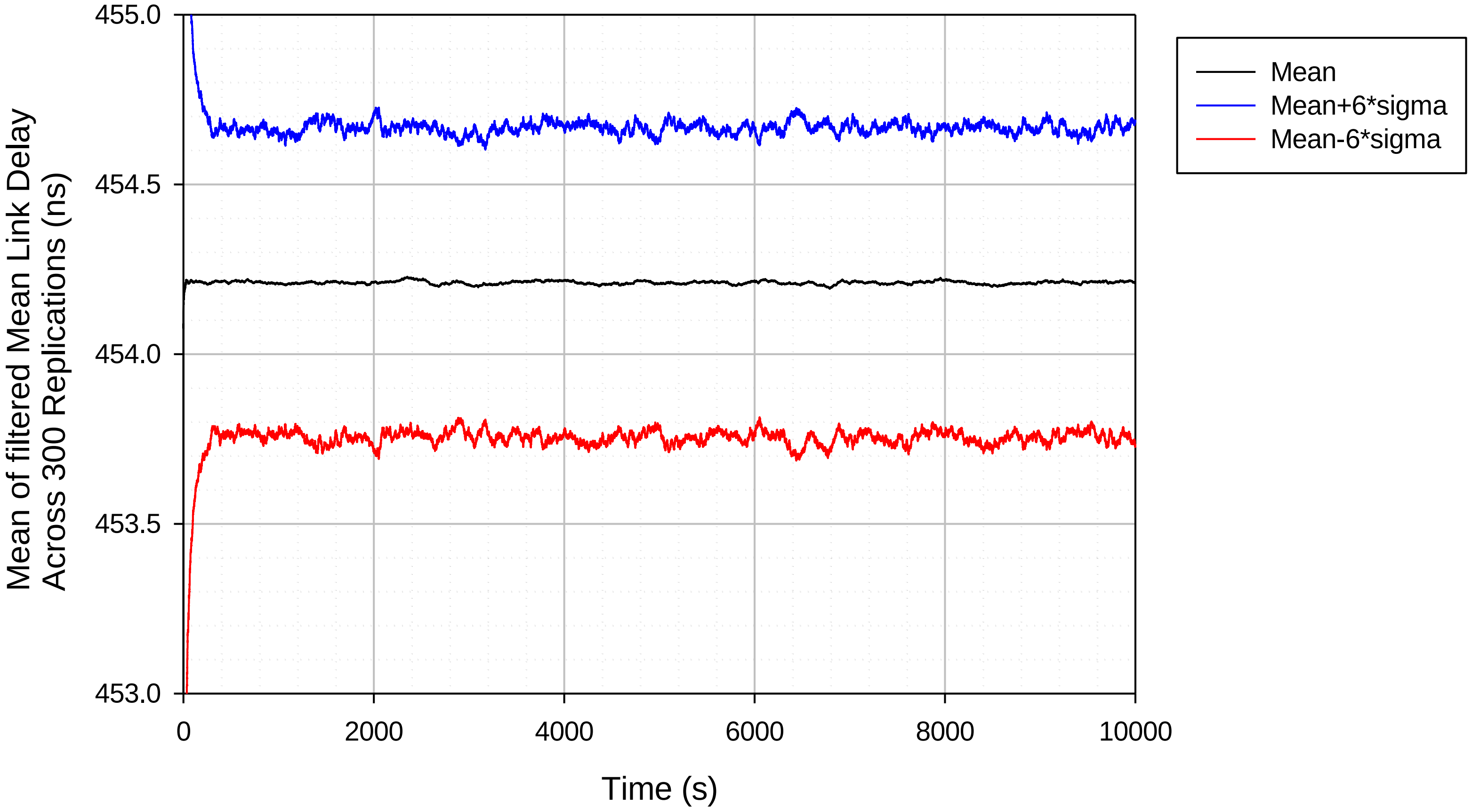
Case01 - Mean Link Delay before IIR Filtering - Replication 300



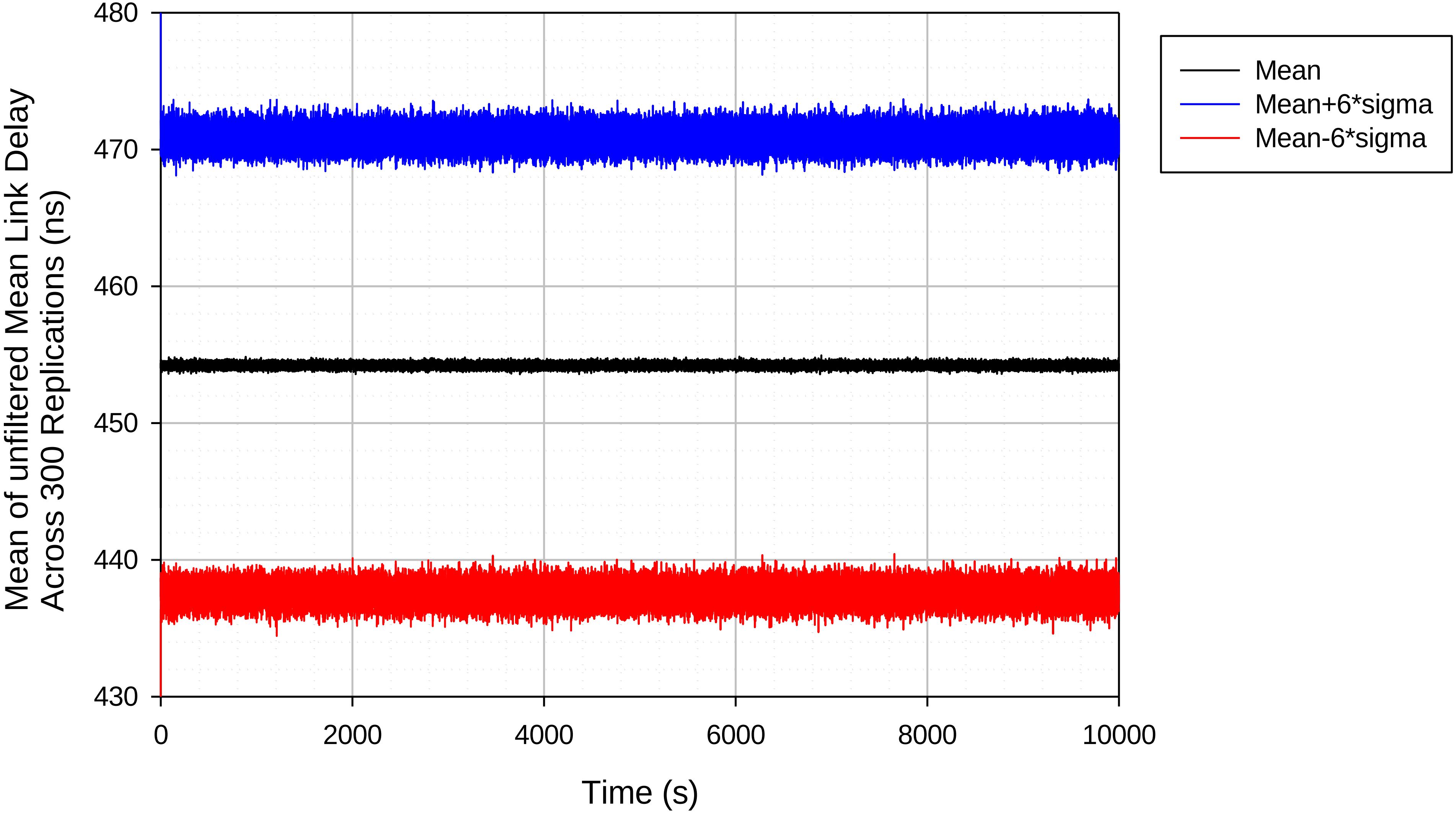
Case01
Mean, mean+6*sigma, mean-6*sigma, of mean link delay after IIR filtering, across 300 replications (Ensemble average)



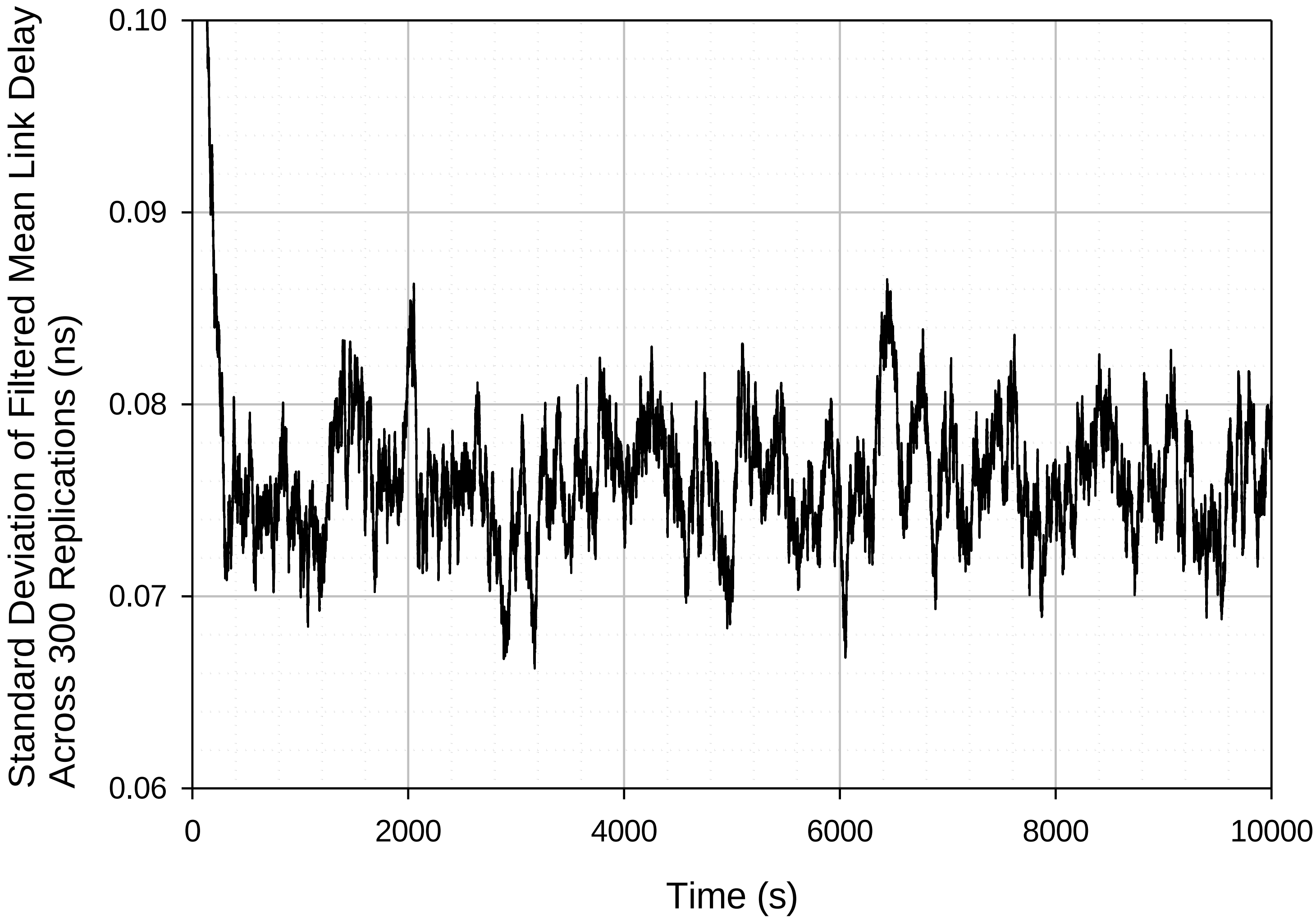
Case01
Mean, mean+6*sigma, mean-6*sigma, of mean link delay after IIR filtering, across 300 replications (Ensemble average)



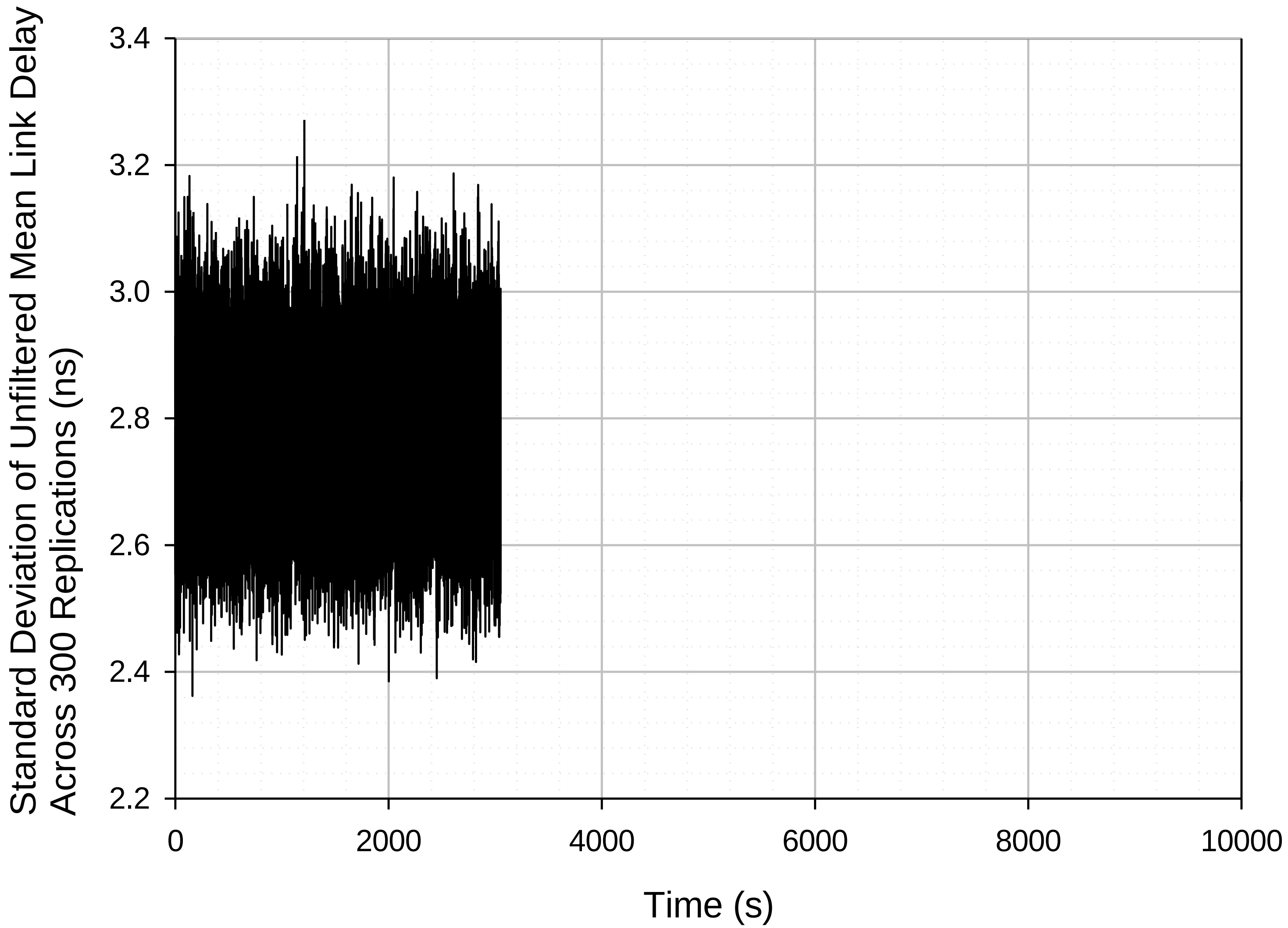
Case01
Mean, mean+6*sigma, mean-6*sigma, of mean link delay before IIR filtering, across 300 replications (Ensemble average)



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

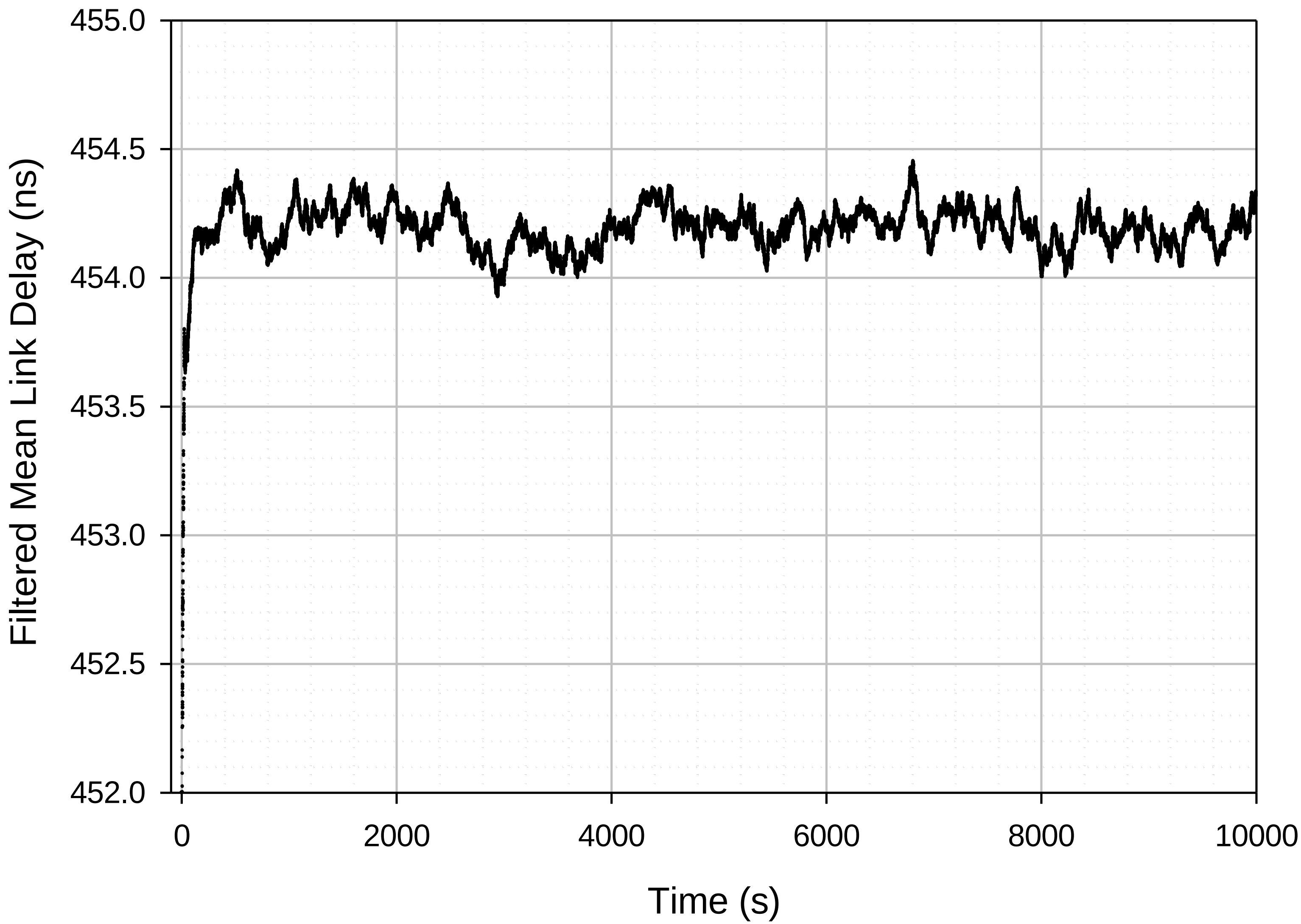


Case01
Standard deviation of mean link delay before IIR filtering, across 300 replications (Ensemble average)

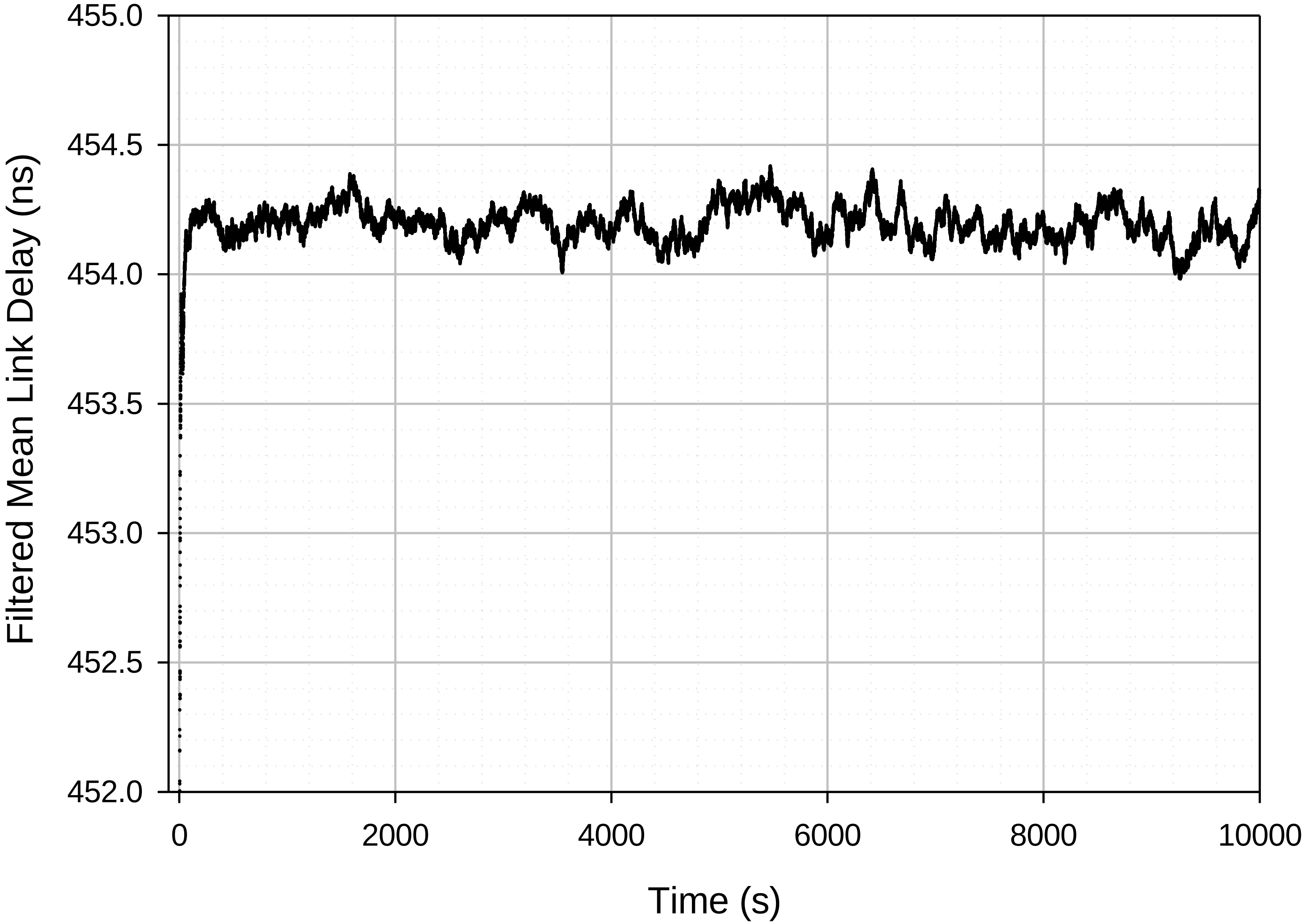


Results for Case 1b – following 10 slides

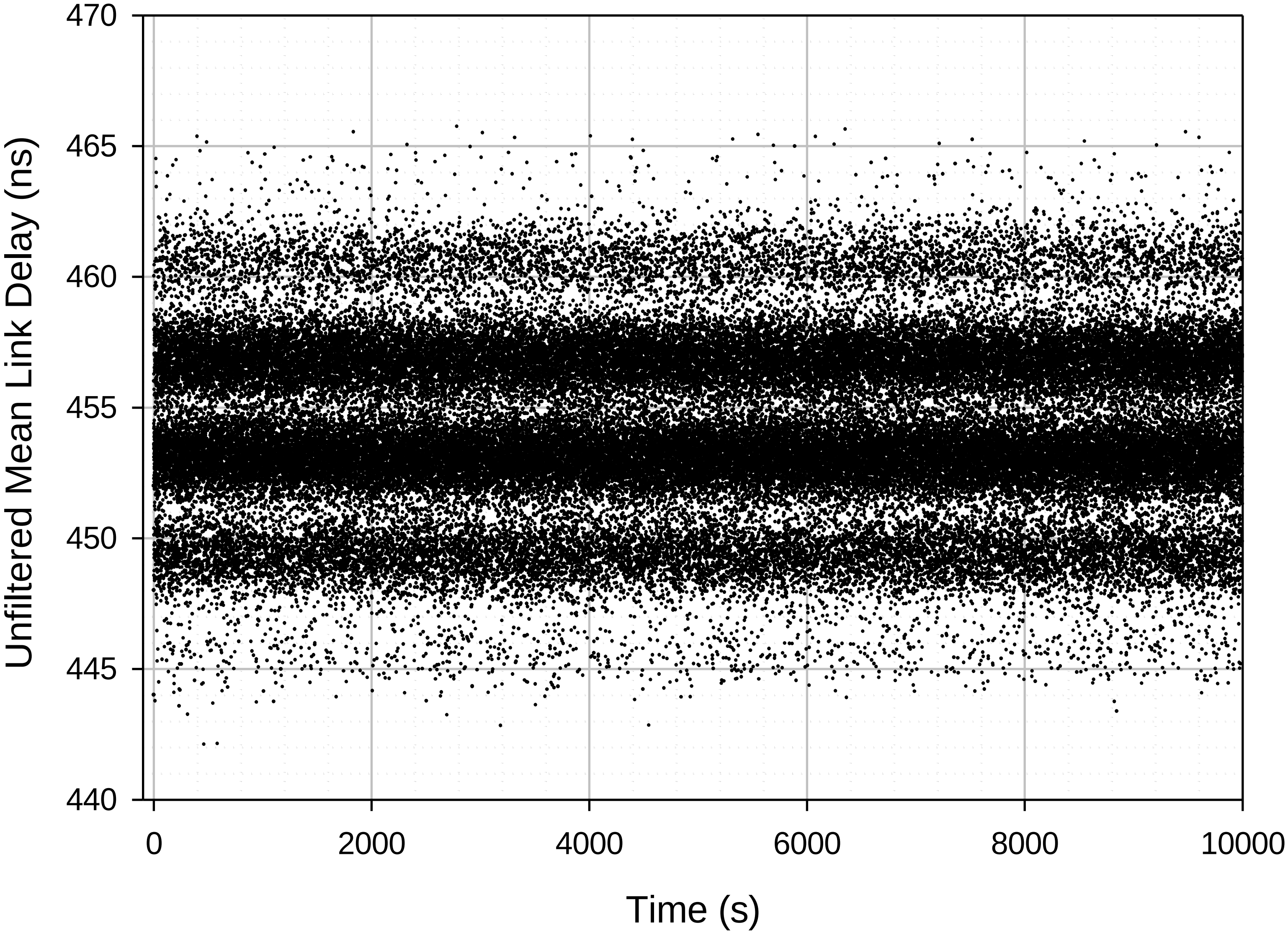
Case01b - Mean Link Delay after IIR Filtering - Replication 1



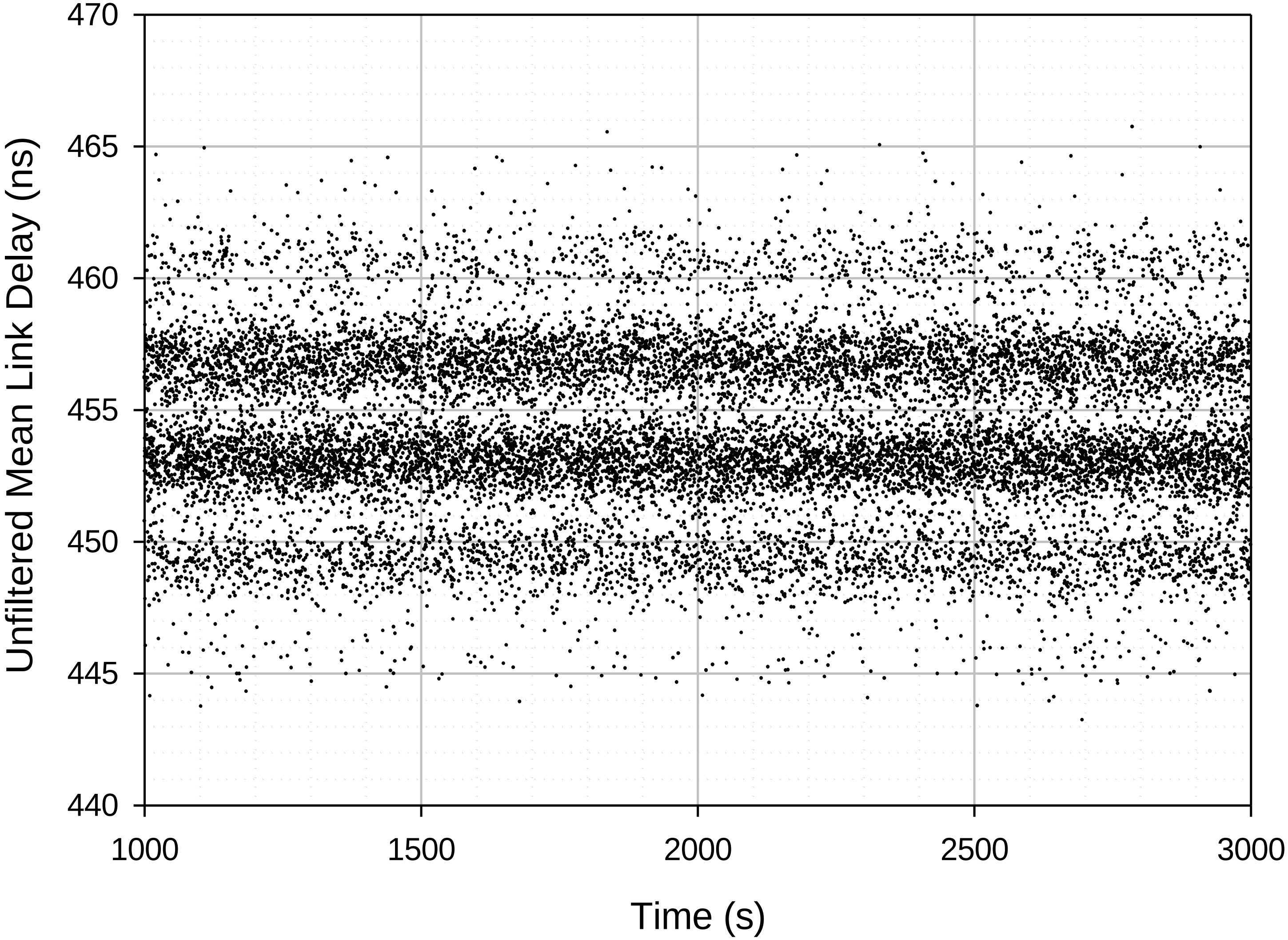
Case01b - Mean Link Delay after IIR Filtering - Replication 300



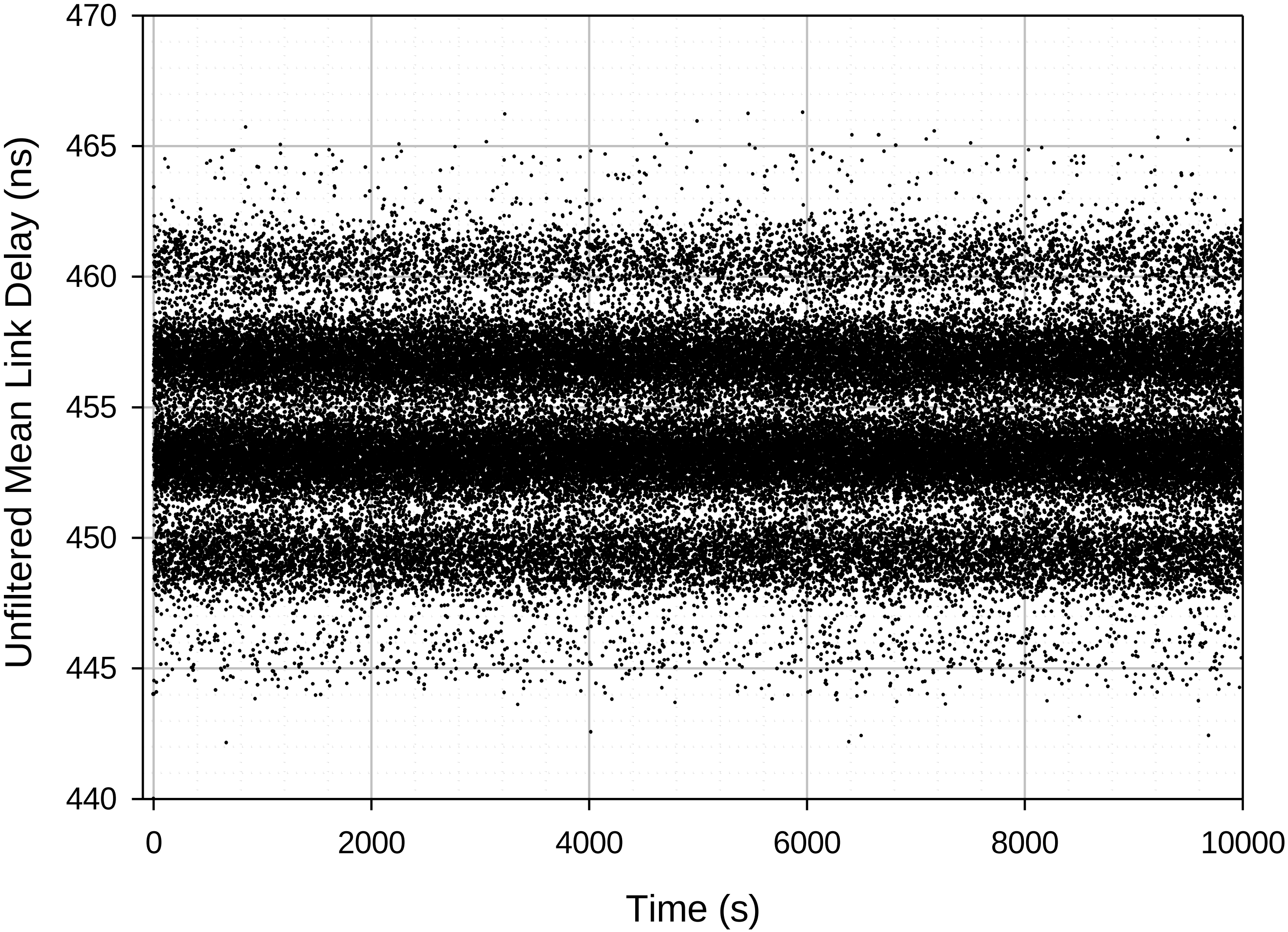
Case01b - Mean Link Delay before IIR Filtering - Replication 1



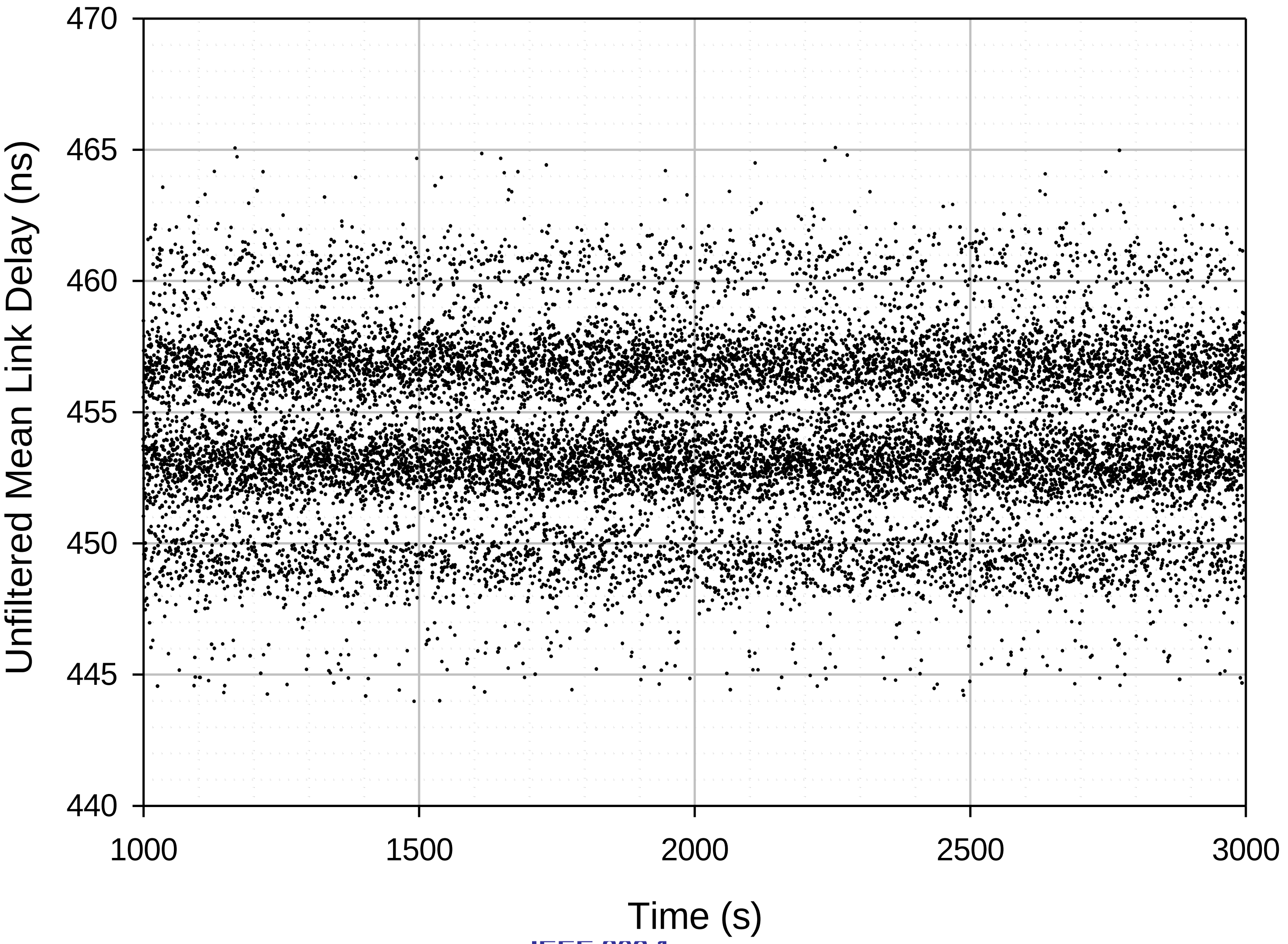
Case01b - Mean Link Delay before IIR Filtering - Replication 1
Detail of 1000 - 3000s



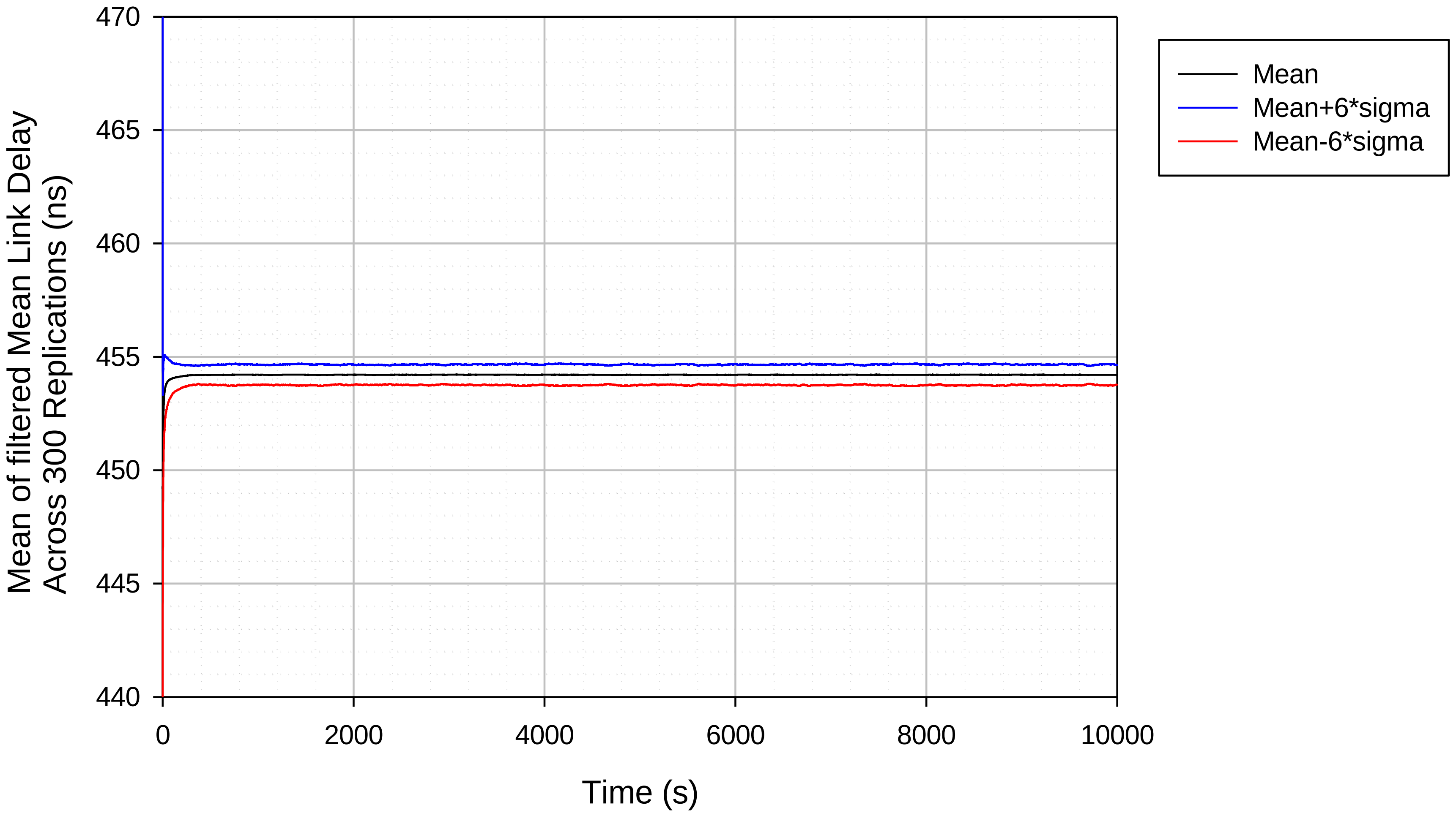
Case01b - Mean Link Delay before IIR Filtering - Replication 300



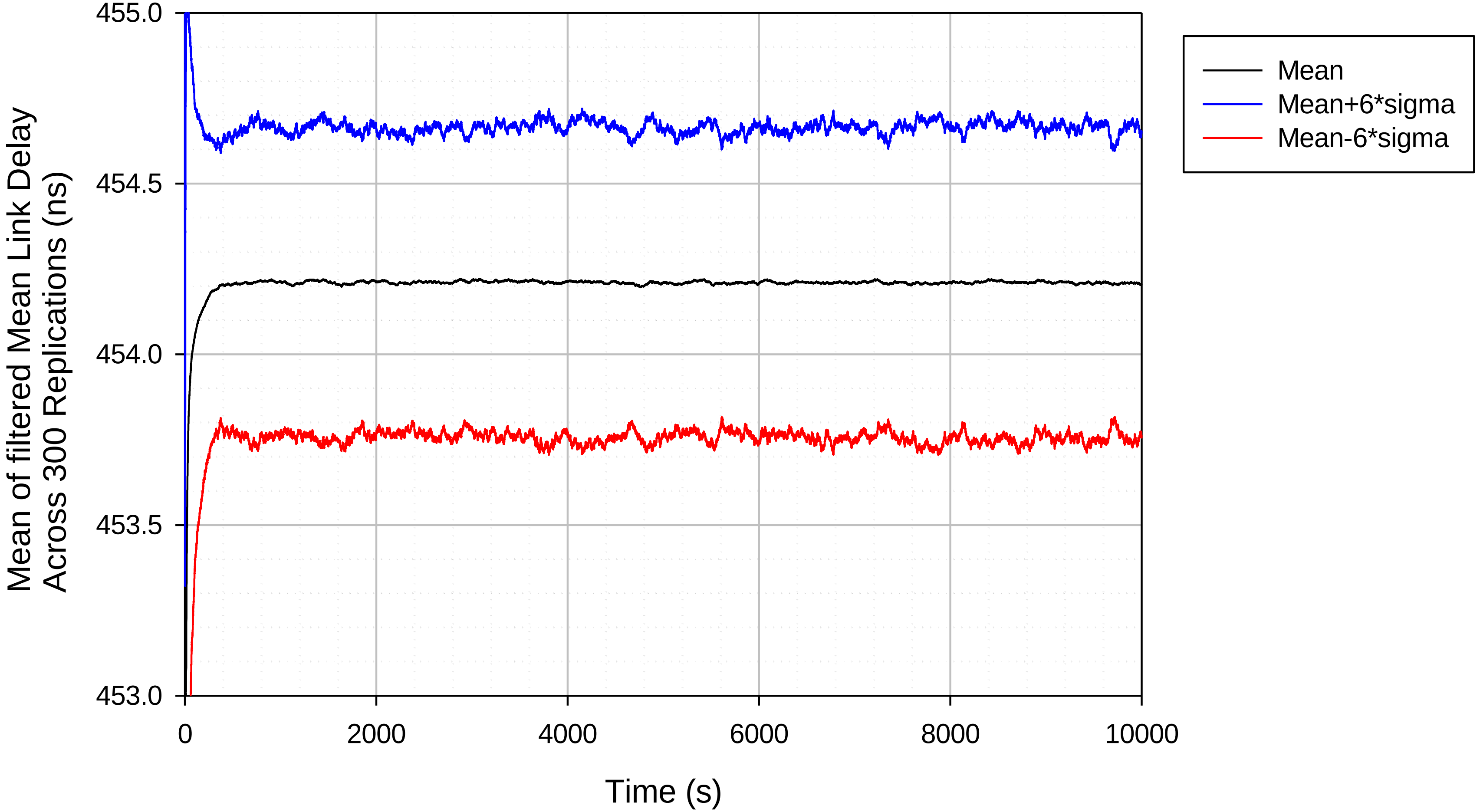
Case01b - Mean Link Delay before IIR Filtering - Replication 300
Detail of 1000 - 3000 s



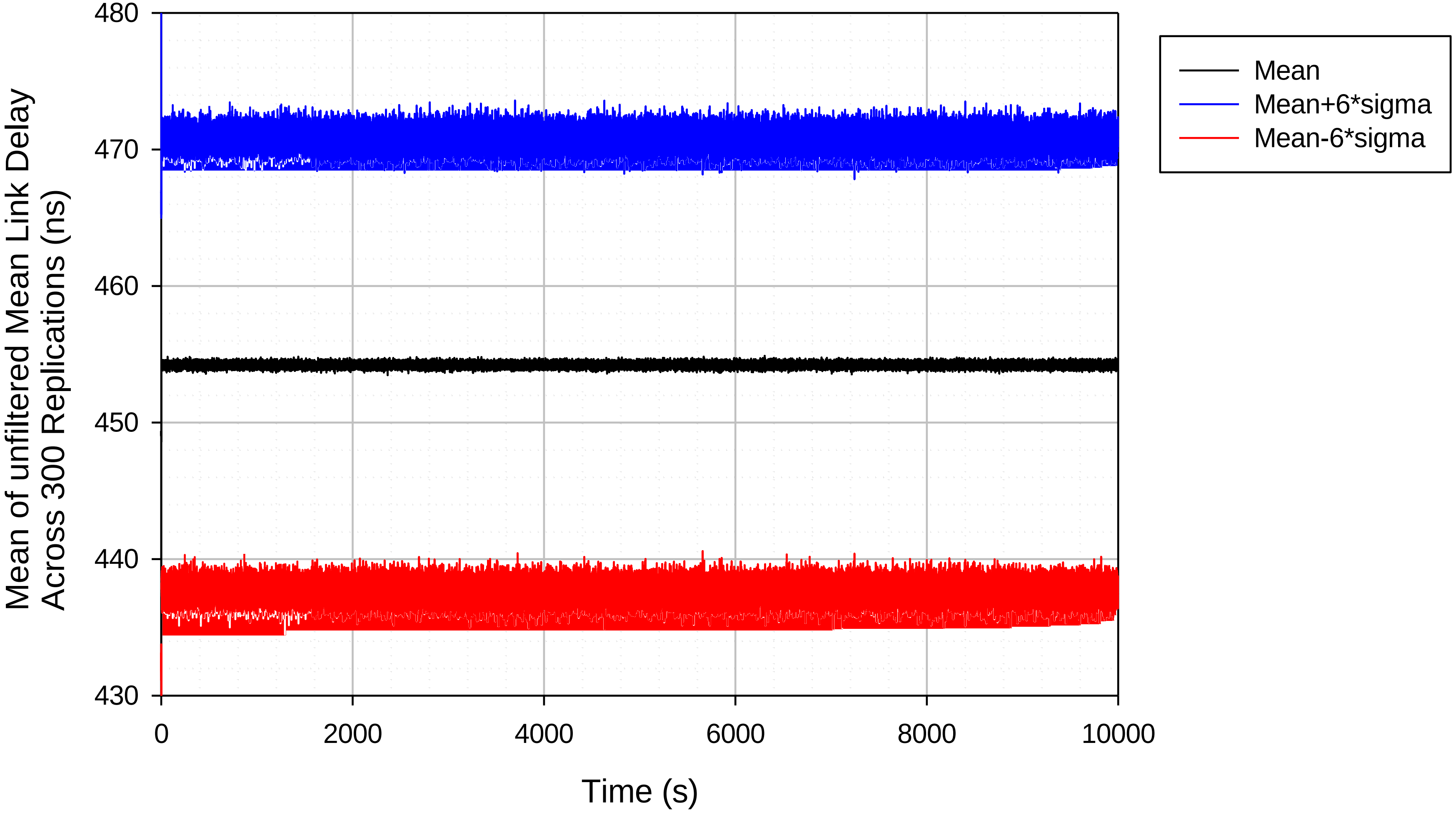
Case01b
Mean, mean+6*sigma, mean-6*sigma, of mean link delay after IIR filtering, across 300 replications (Ensemble average)



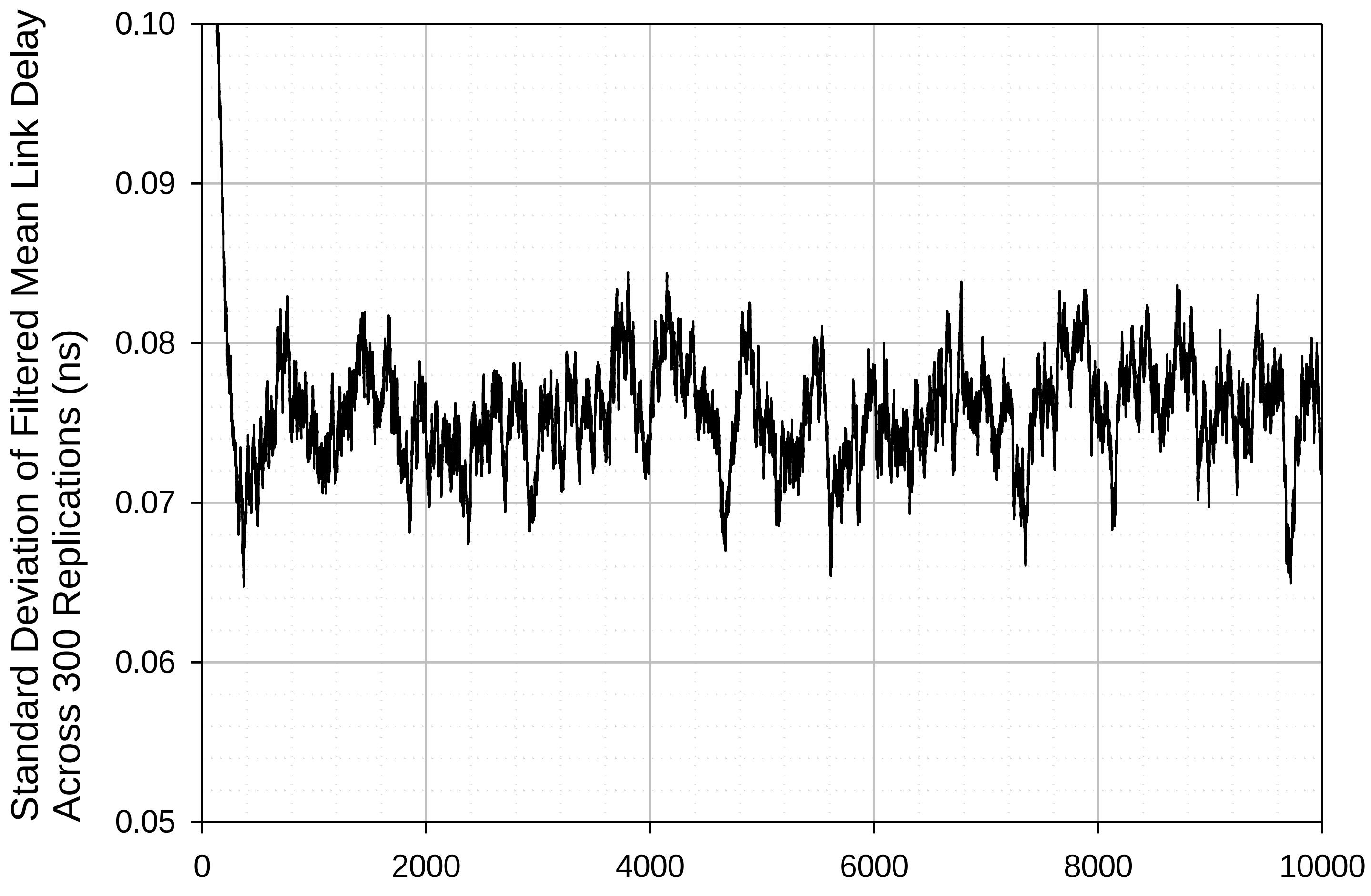
Case01b
Mean, mean+6*sigma, mean-6*sigma, of mean link delay after IIR filtering, across 300 replications (Ensemble average)



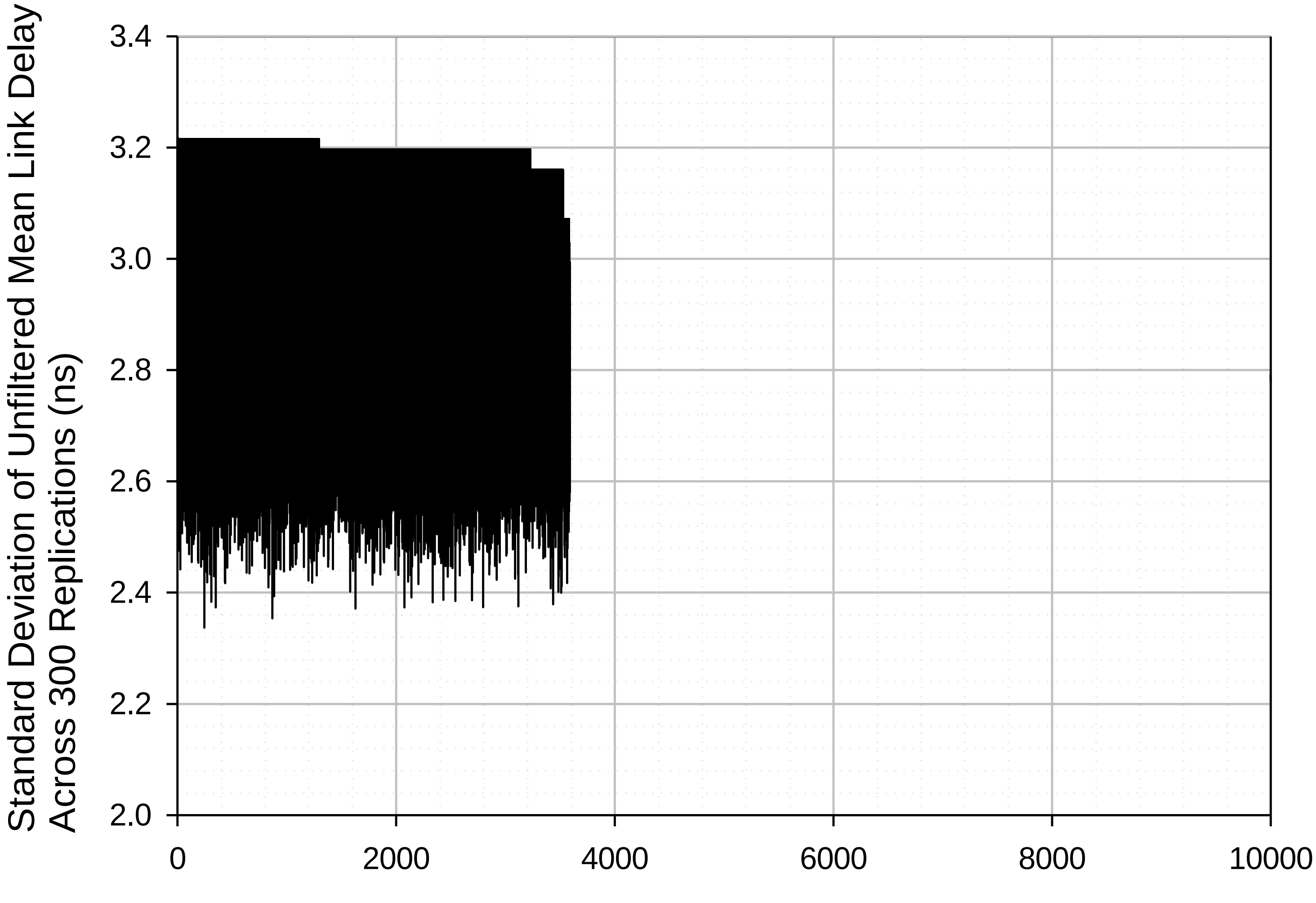
Case01b
Mean, mean+6*sigma, mean-6*sigma, of mean link delay before IIR filtering, across 300 replications (Ensemble average)



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

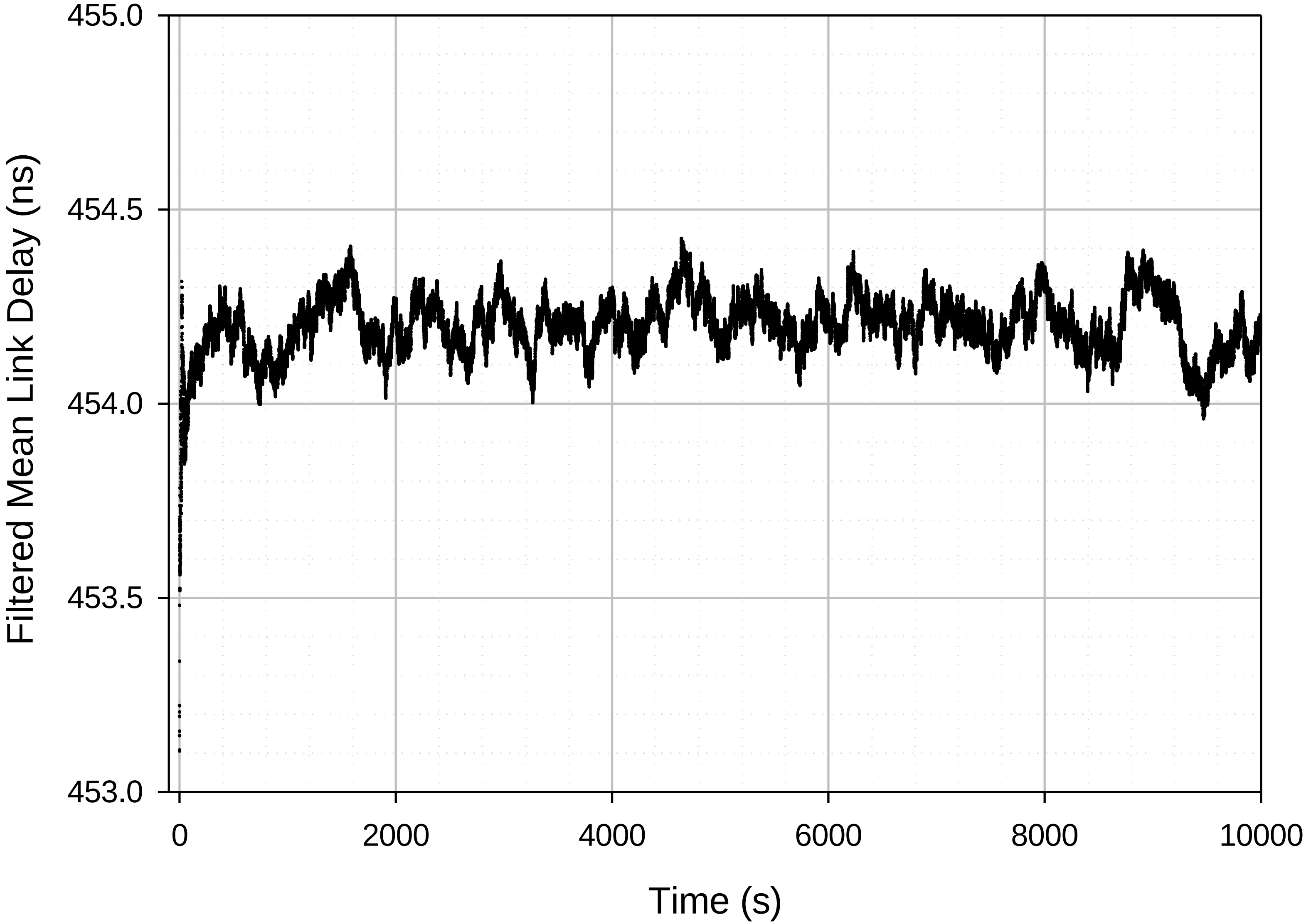


Case01b
Standard deviation of mean link delay before IIR filtering, across 300 replications (Ensemble average)

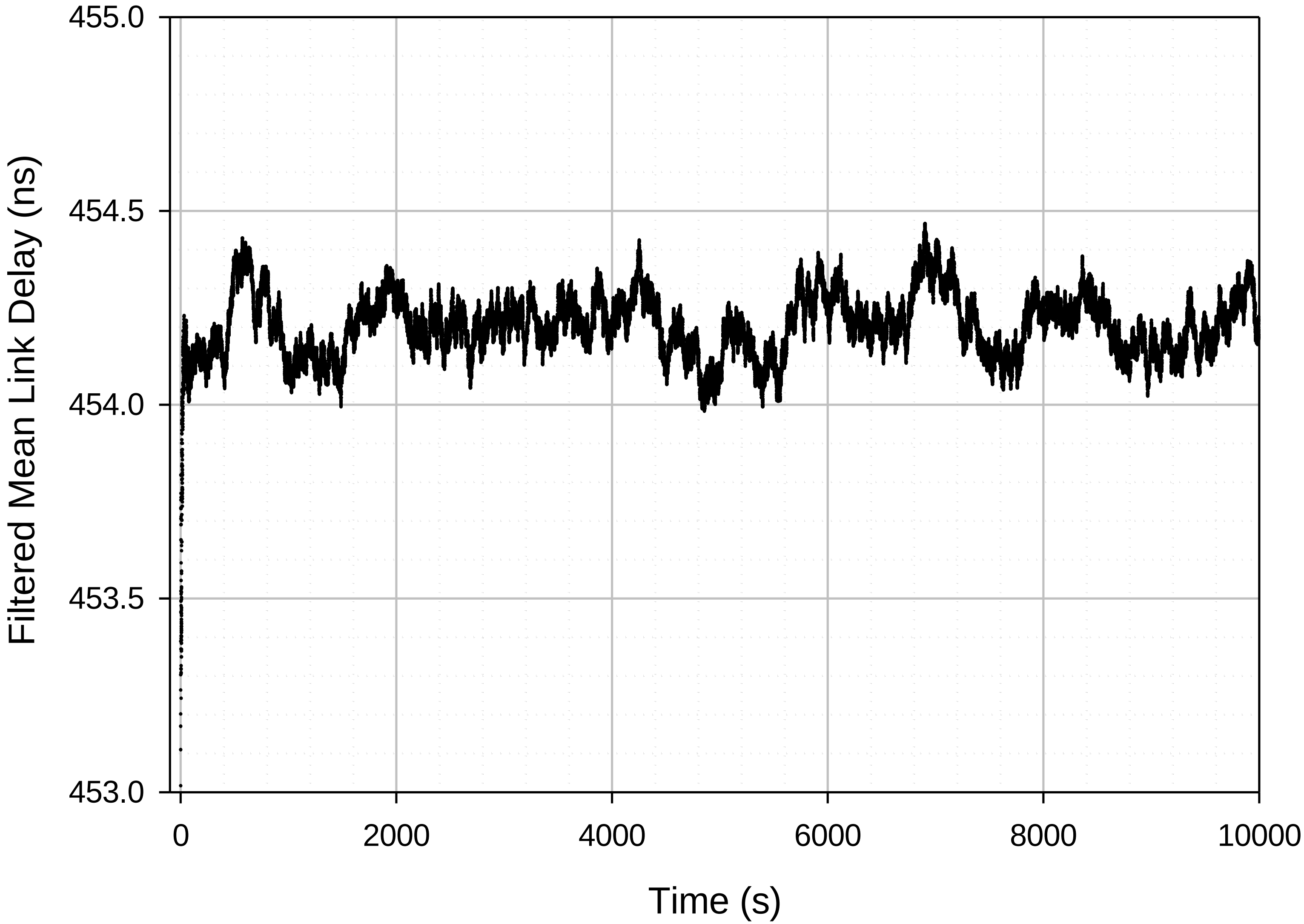


Results for Case 1c – following 10 slides

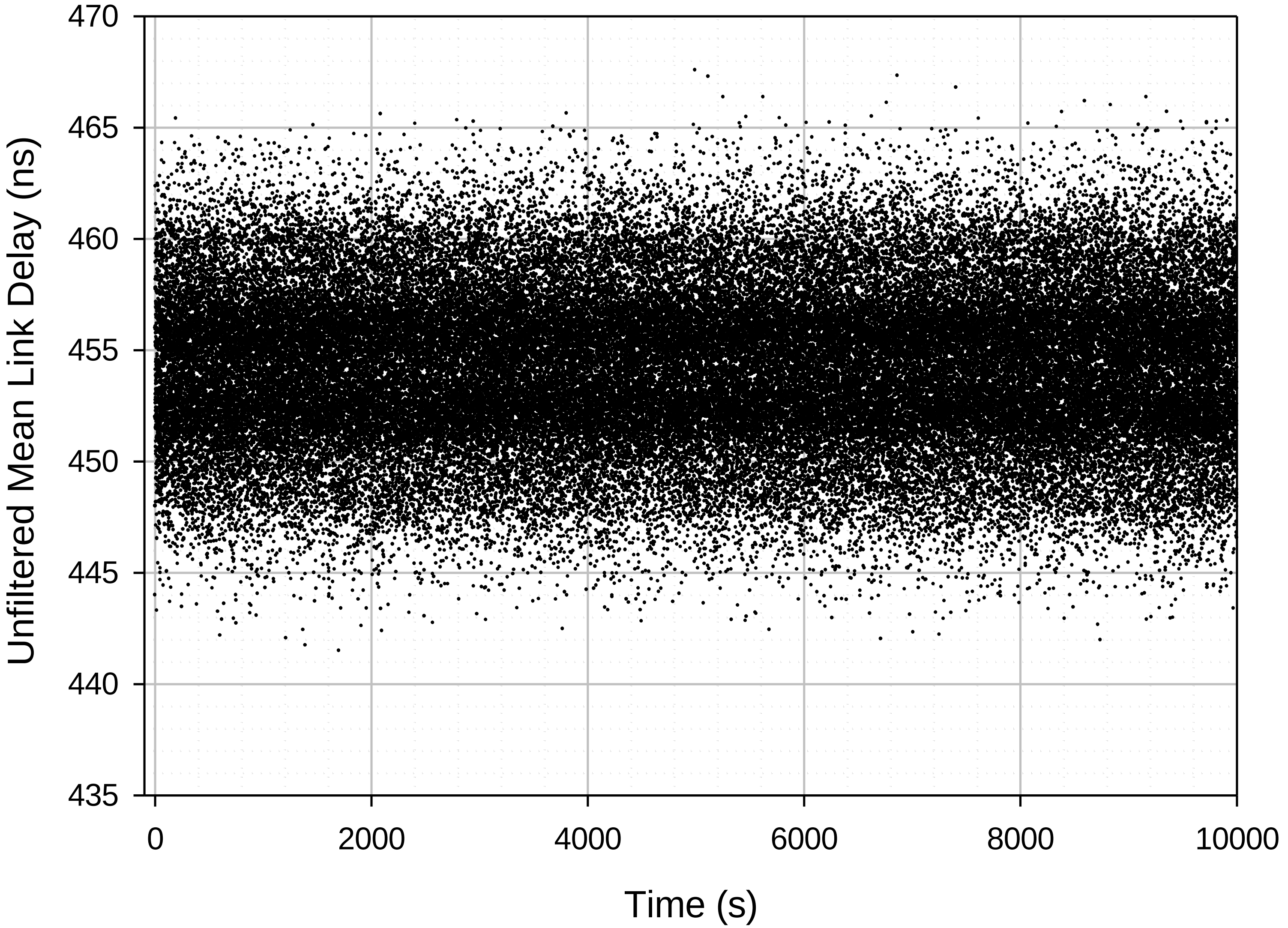
Case01c - Mean Link Delay after IIR Filtering - Replication 1



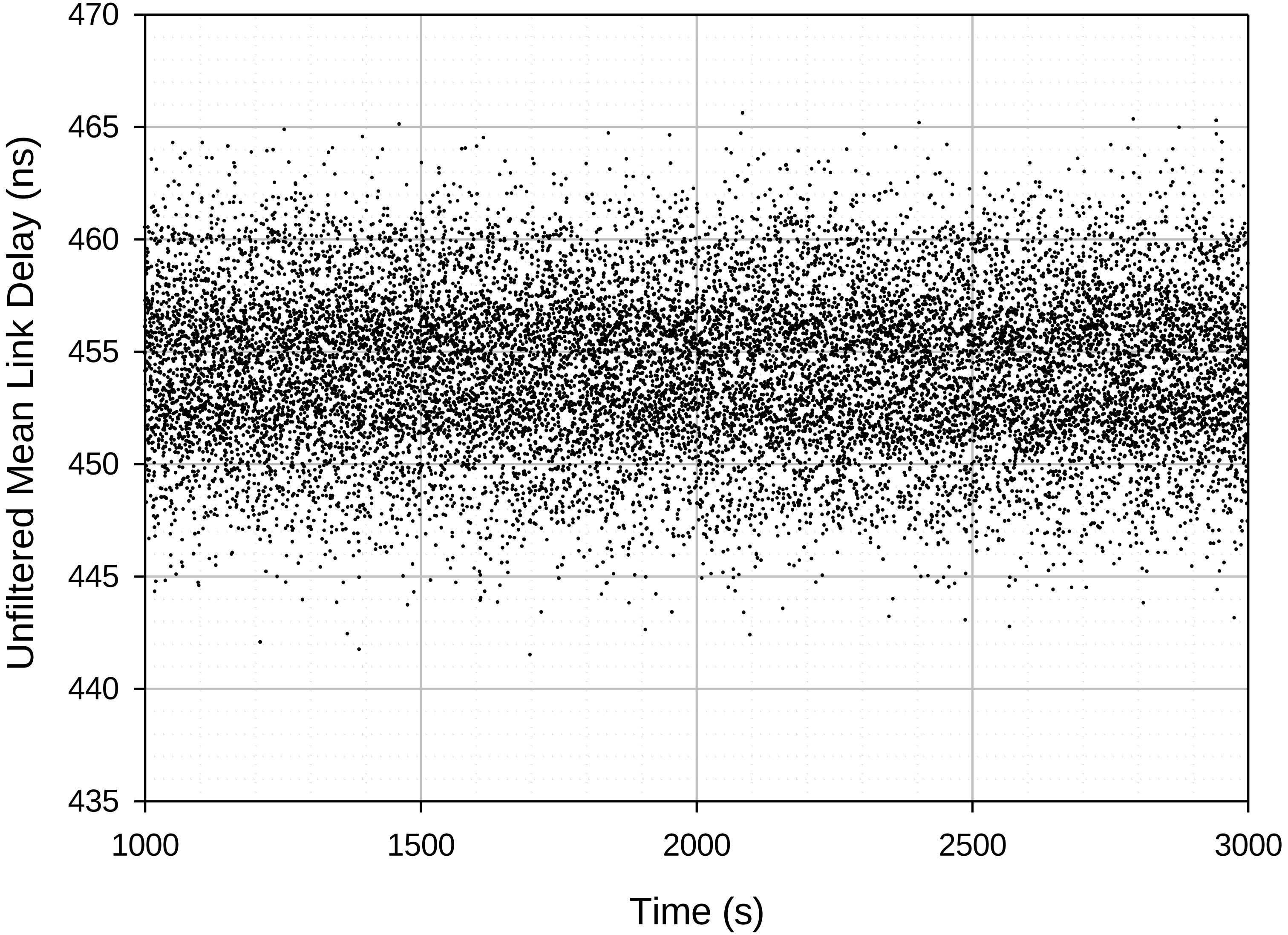
Case01c - Mean Link Delay after IIR Filtering - Replication 300



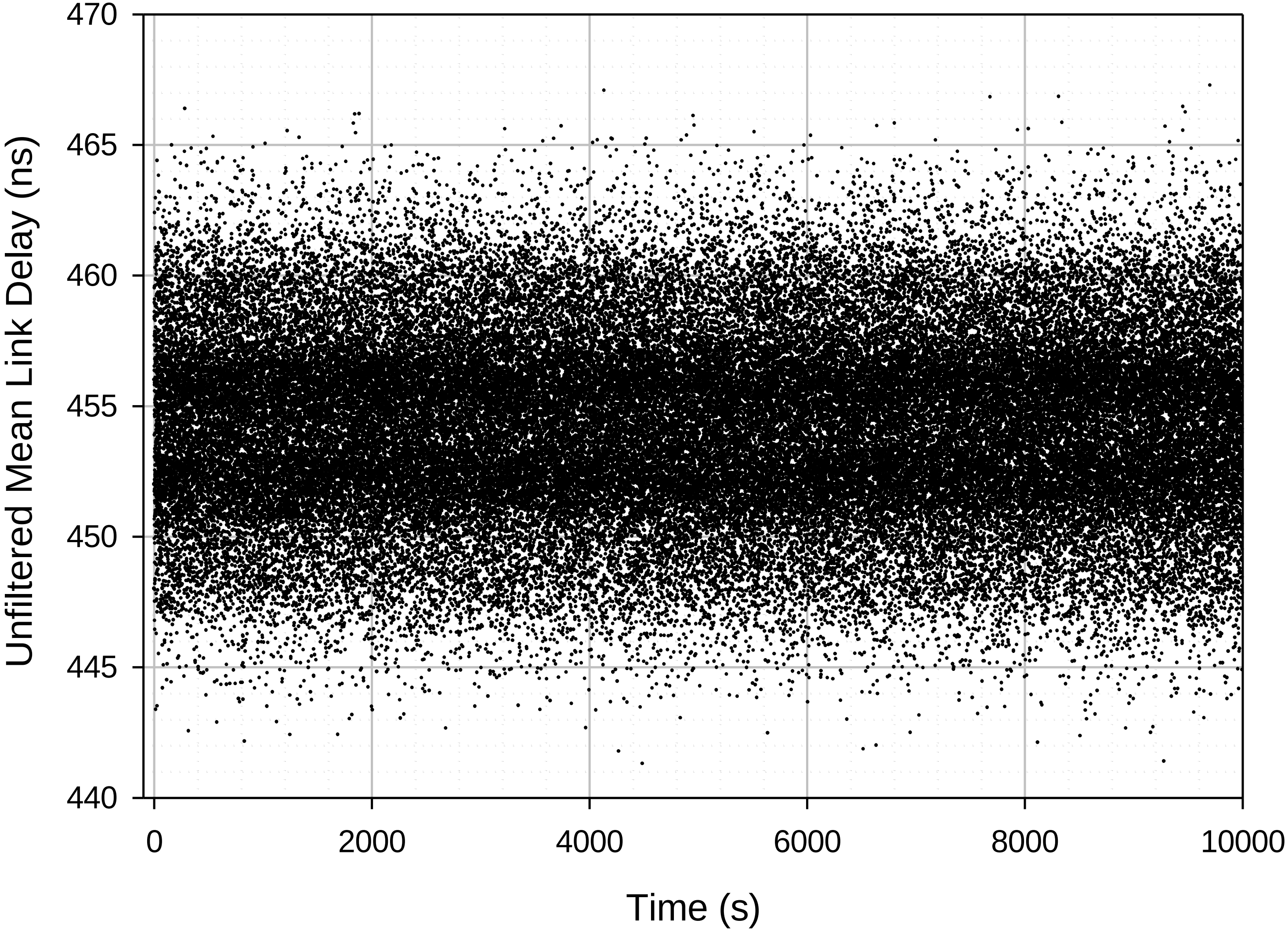
Case01c - Mean Link Delay before IIR Filtering - Replication 1



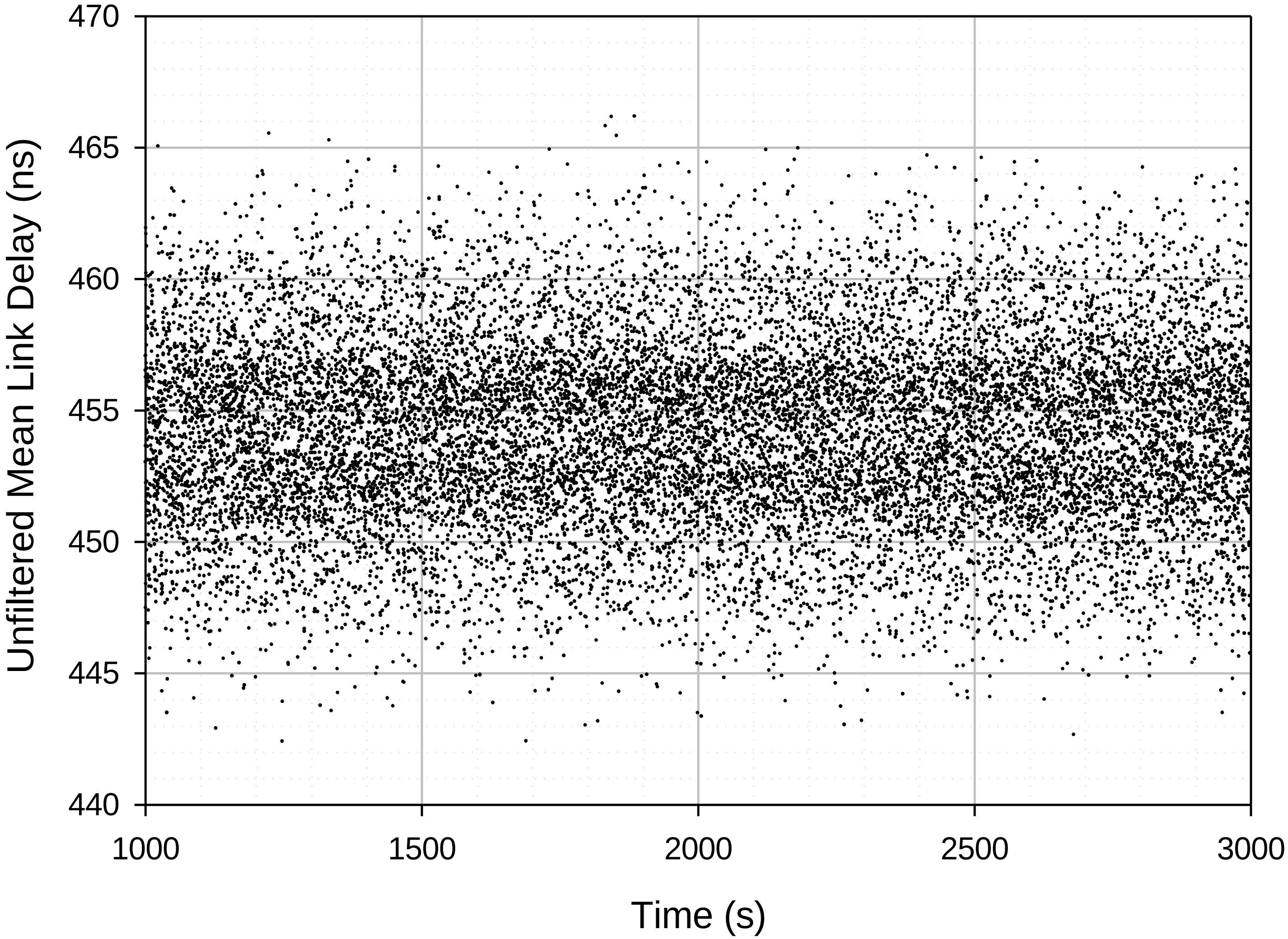
Case01c - Mean Link Delay before IIR Filtering - Replication 1



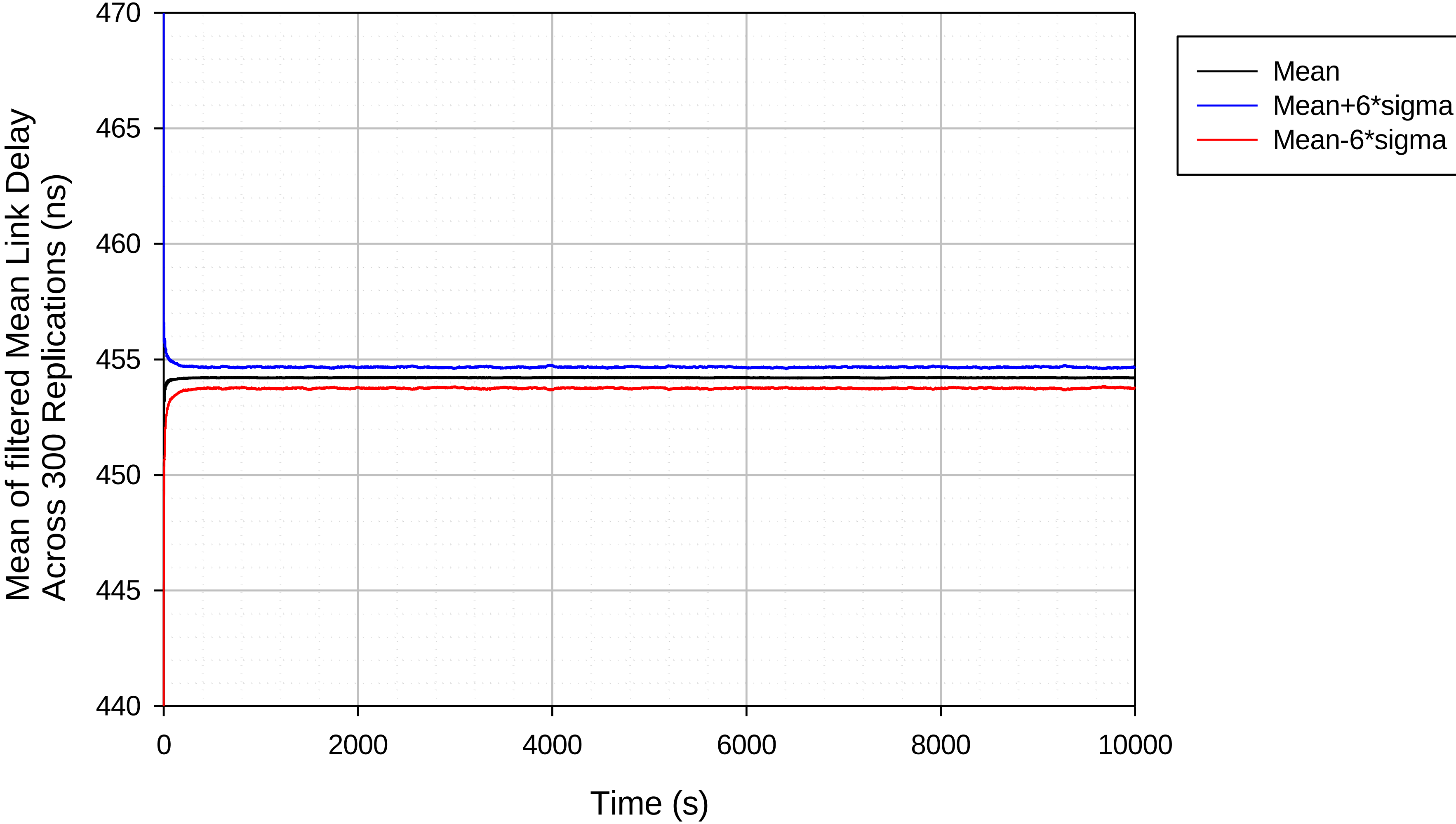
Case01c - Mean Link Delay before IIR Filtering - Replication 300



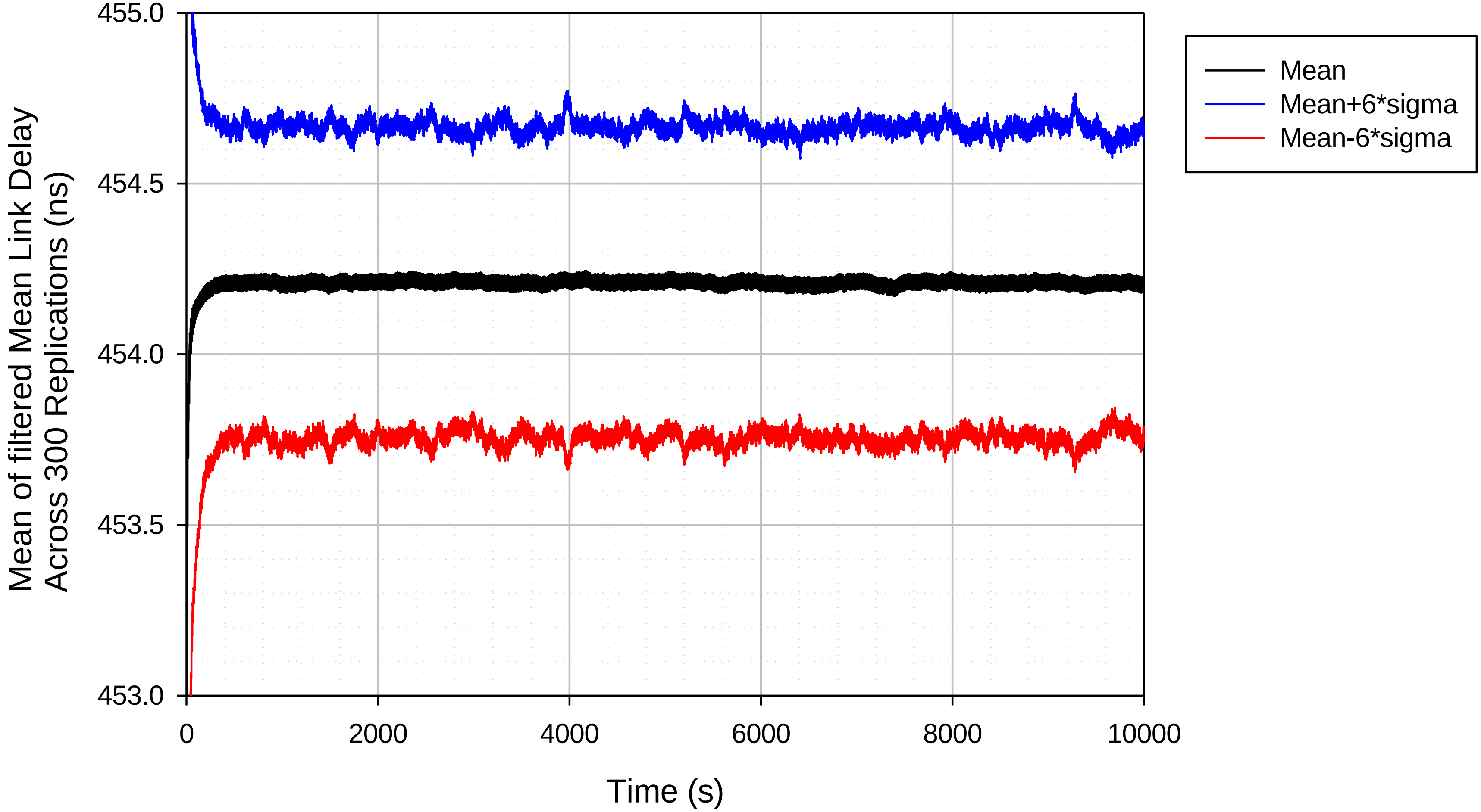
Case01c - Mean Link Delay before IIR Filtering - Replication 300
Detail of 1000 - 3000 s



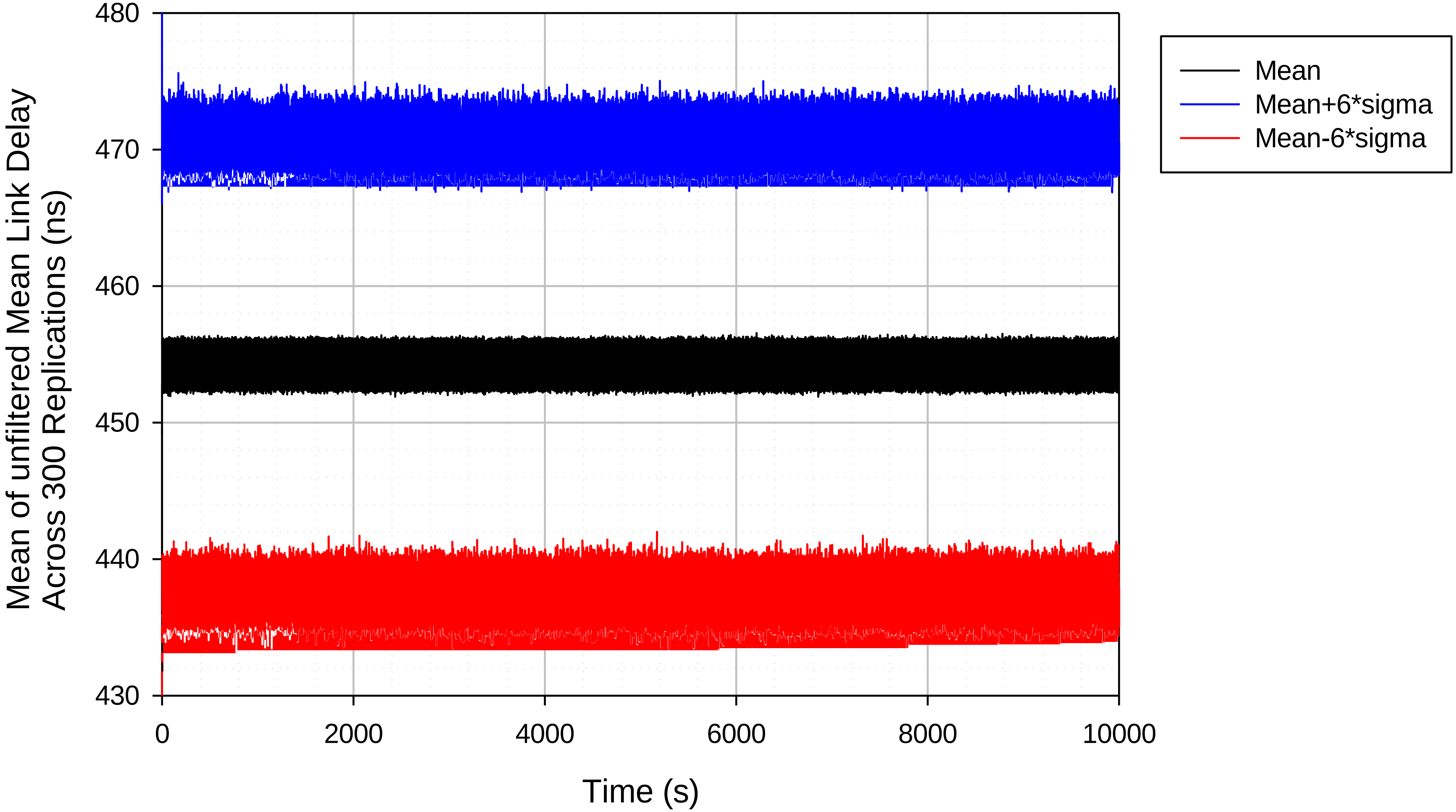
Case01c
Mean, mean+6*sigma, mean-6*sigma, of mean link delay after IIR filtering, across 300 replications (Ensemble average)



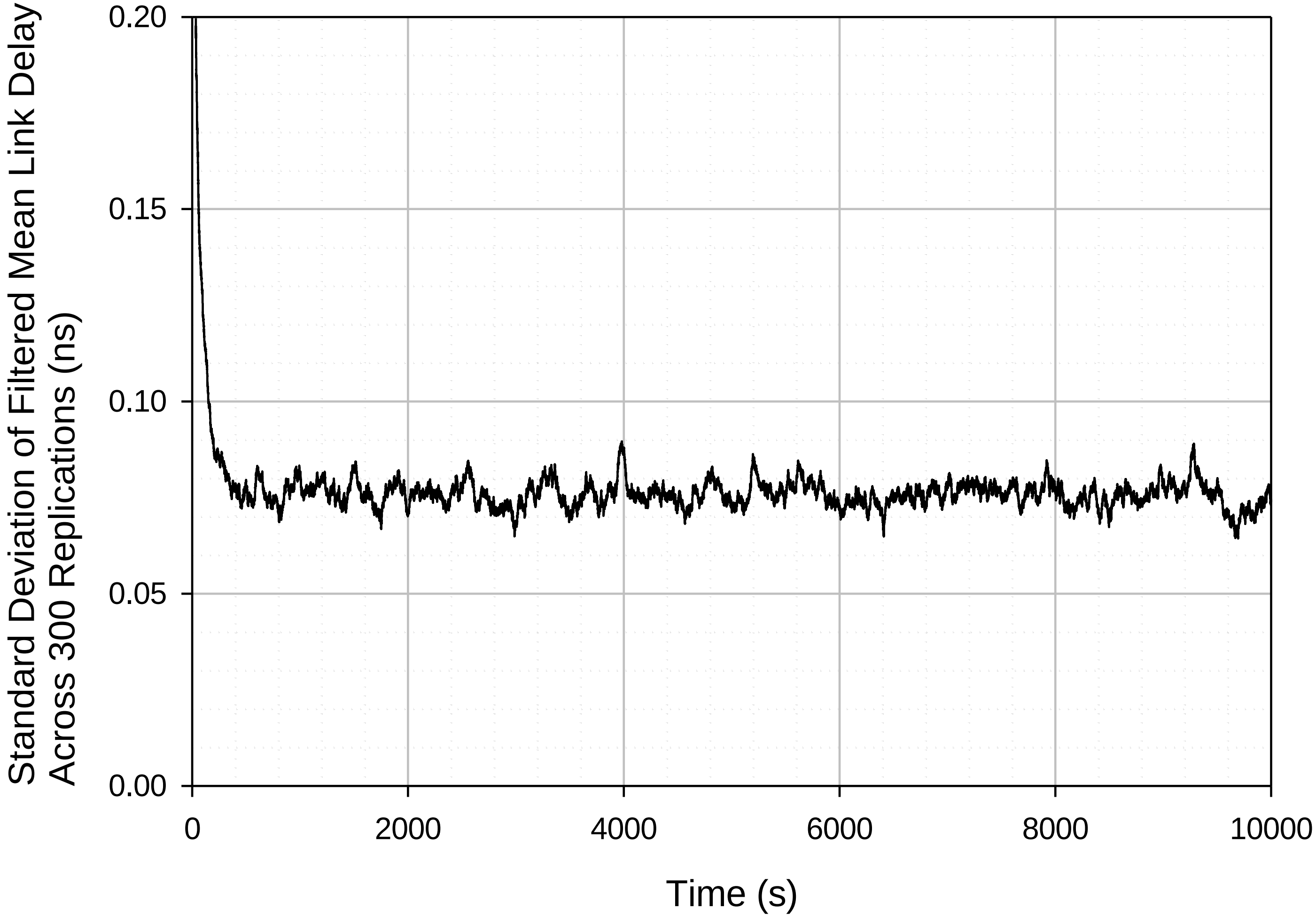
Case01c
Mean, mean+6*sigma, mean-6*sigma, of mean link delay after IIR filtering, across 300 replications (Ensemble average)



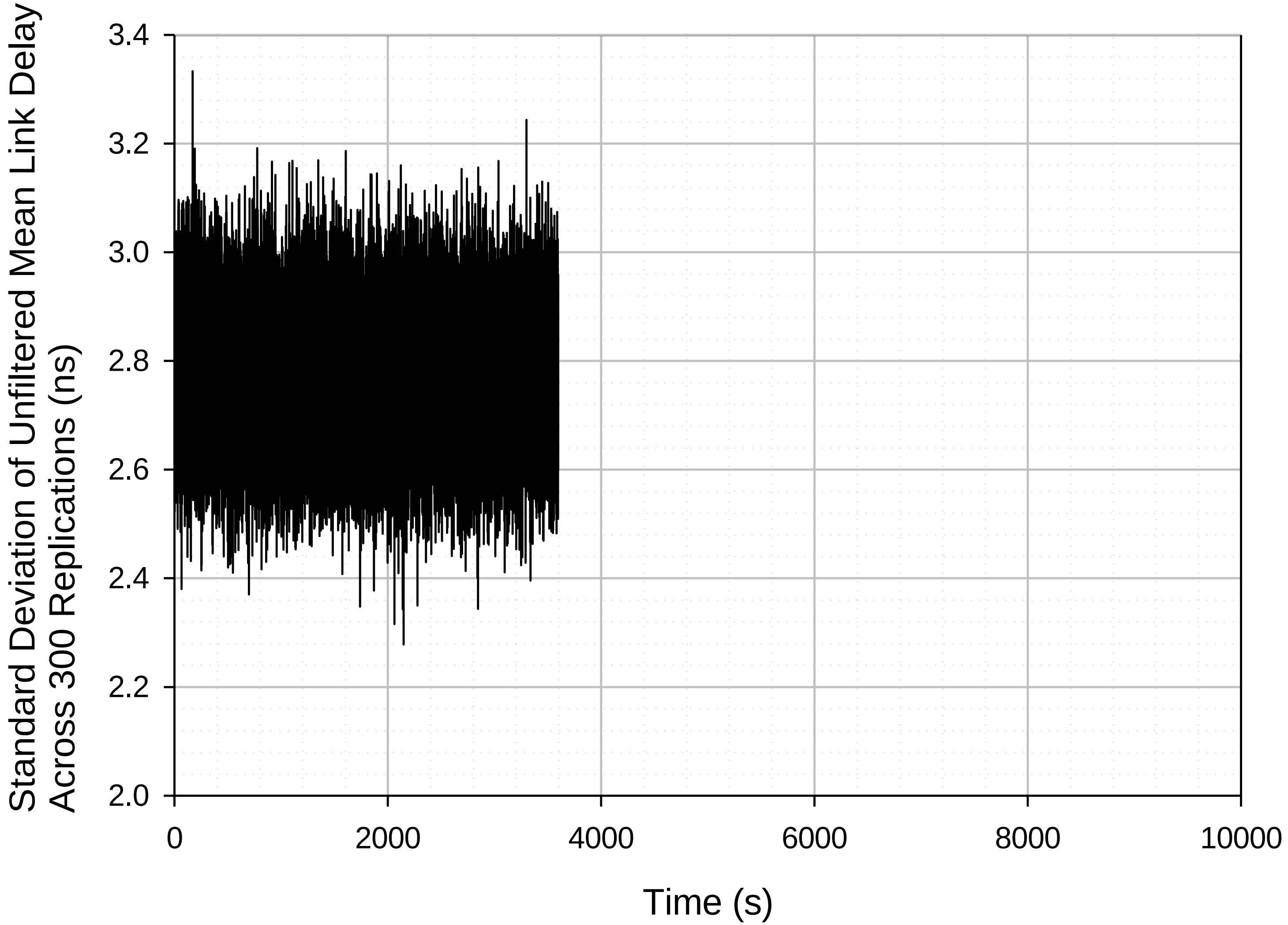
- Case01c
  Mean, mean+6*sigma, mean-6*sigma, of mean link delay before IIR filtering, across 300 replications (Ensemble average)



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

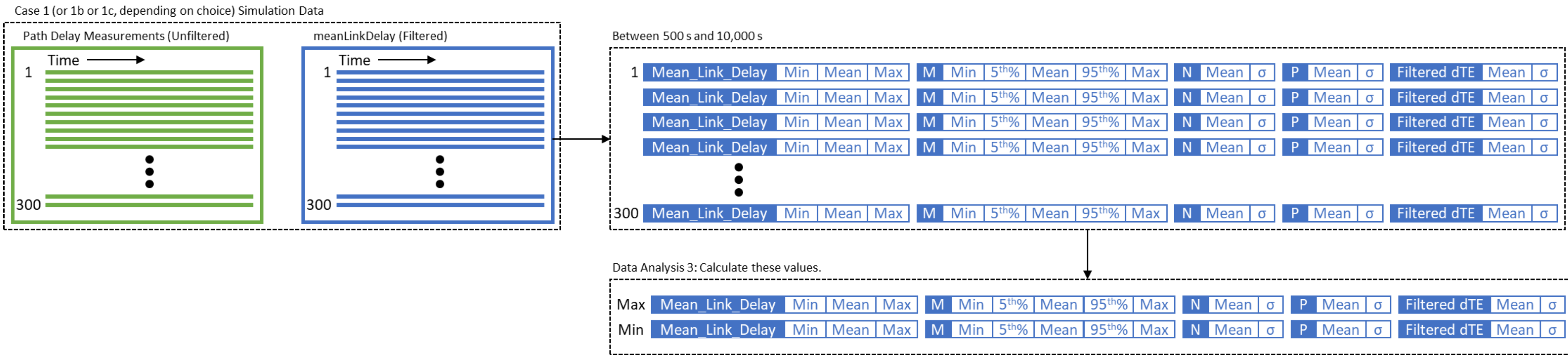


Case01c
Standard deviation of mean link delay before IIR filtering, across 300 replications (Ensemble average)



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 ±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 453.862 ~~451.946~~ ns and the maximum is 454.557 ~~456.198~~ ns
  - For case 1b, the minimum is 453.855 ~~451.973~~ ns and the maximum is 454.532 ~~456.191~~ ns
  - For case 1c, the minimum is 453.858 ~~451.935~~ ns and the maximum is 454.575 ~~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, and P, the requirements of Tables 13 and 14 of [1] are shown in red in the results tables on slides 90 and 91 (for M), 92 (for N), 93 (for P), and 94 (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

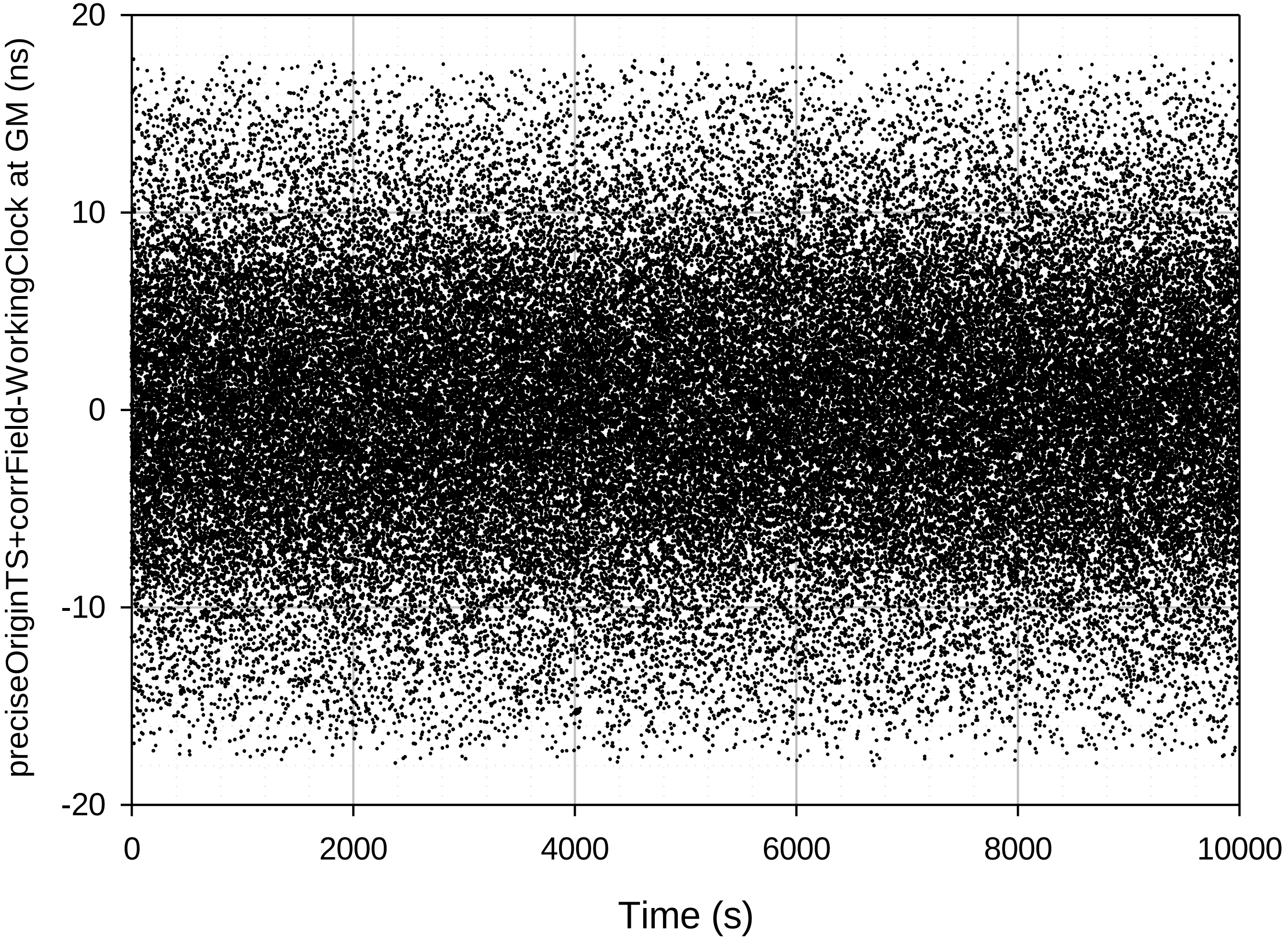
- All of the relevant quantities meet the requirements of Tables 13
  - The Table 13 requirements on M indicate that the range around the measured mean within which 90% of the measurements fall must be ± 10 ns, and the range within which 100% of the measurements fall must be ± 20 ns
  - The measured 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 95th 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

Experiment 1, Data Analysis 3 - 5

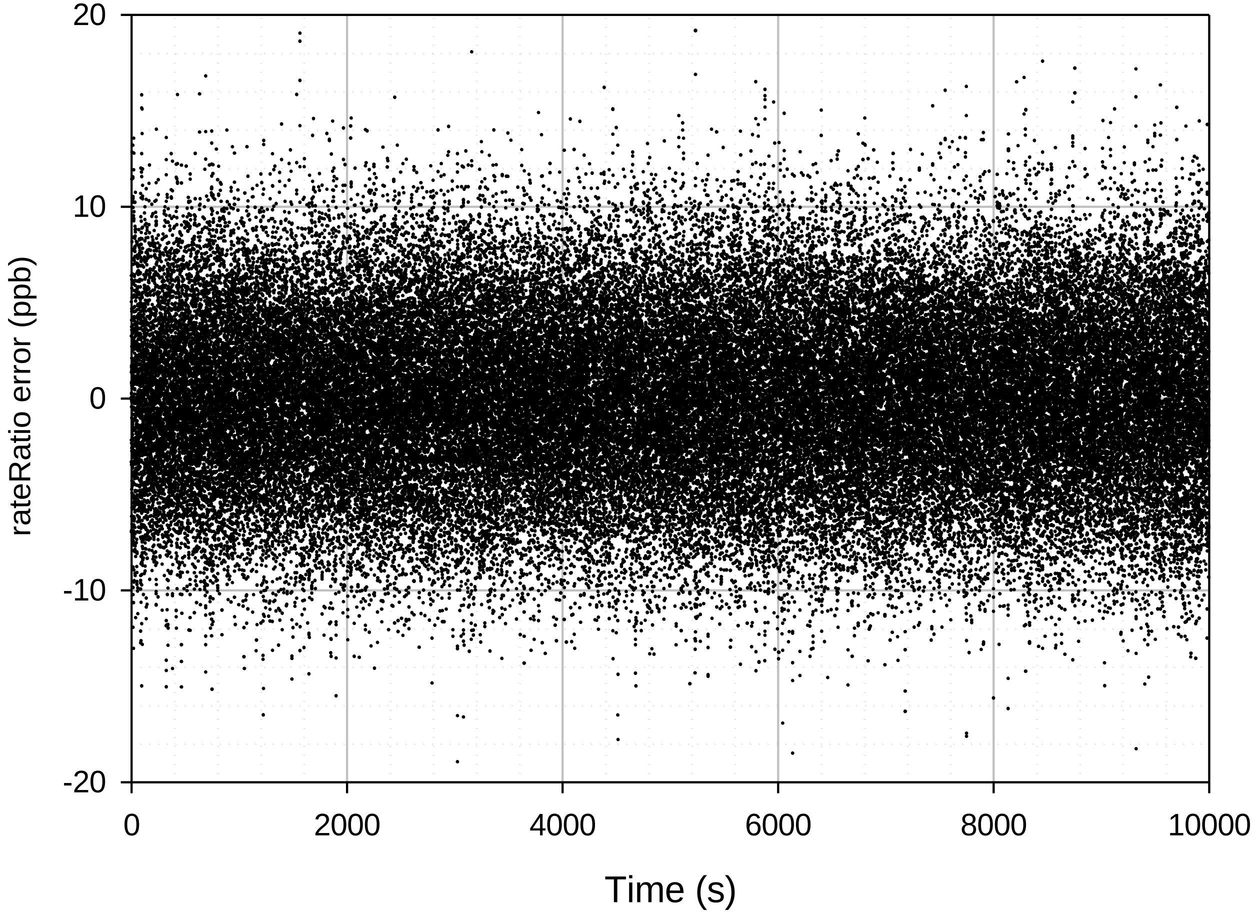
- With one exception, all the filtered dTE results meet the requirements of Table 14 ($\pm$15 ns)
  - The one exception is the result for the maximum filtered dTE, taken both over time and over the 300 replications of the simulation (i.e., 15.327 ns)
  - Examination of the simulation results (numerical output) indicates that this exceedance of 15 ns occurred at exactly one data point on exactly 2 of the 300 replications
    - Maximum dTE of 15.127 ns on replication 239 at 2791 s
    - Maximum dTE of 15.327 ns on replication 244 at 2436 s (omitting exceedances before 2 s due to an initial transient)

Plots for Case 1 – following 4 slides

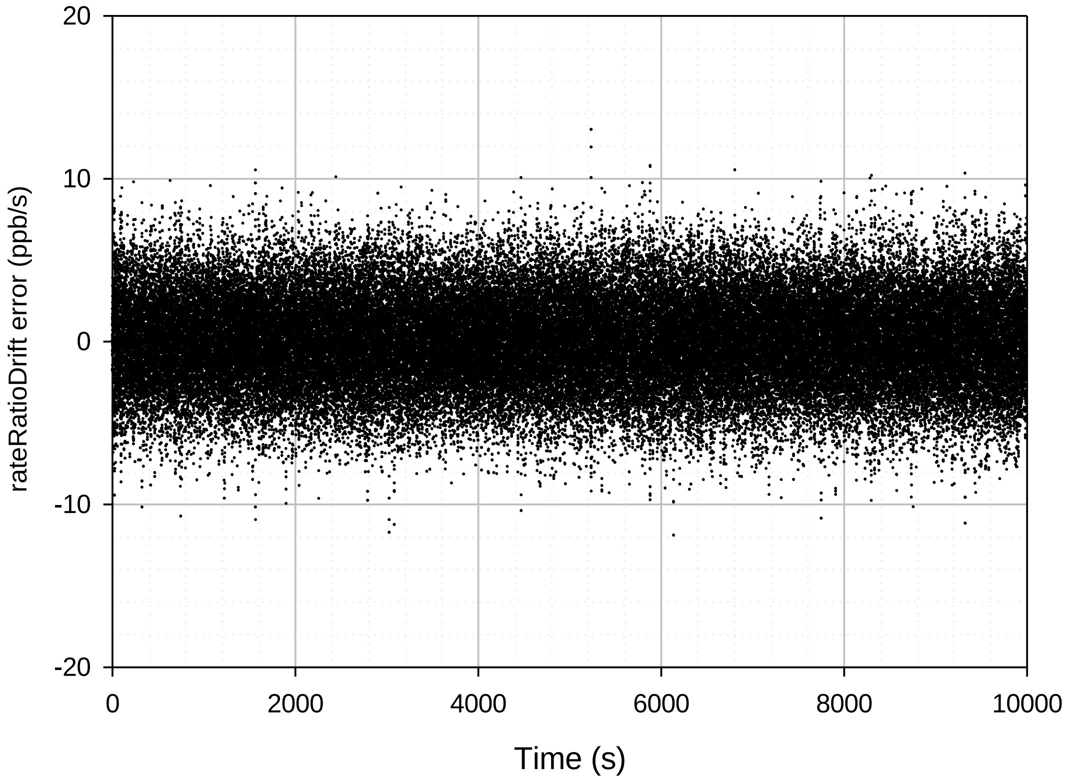
Case 1, Replication 1
preciseOriginTimestamp + correctionField - Working Clock at GM at transmission of Sync message
Node 3



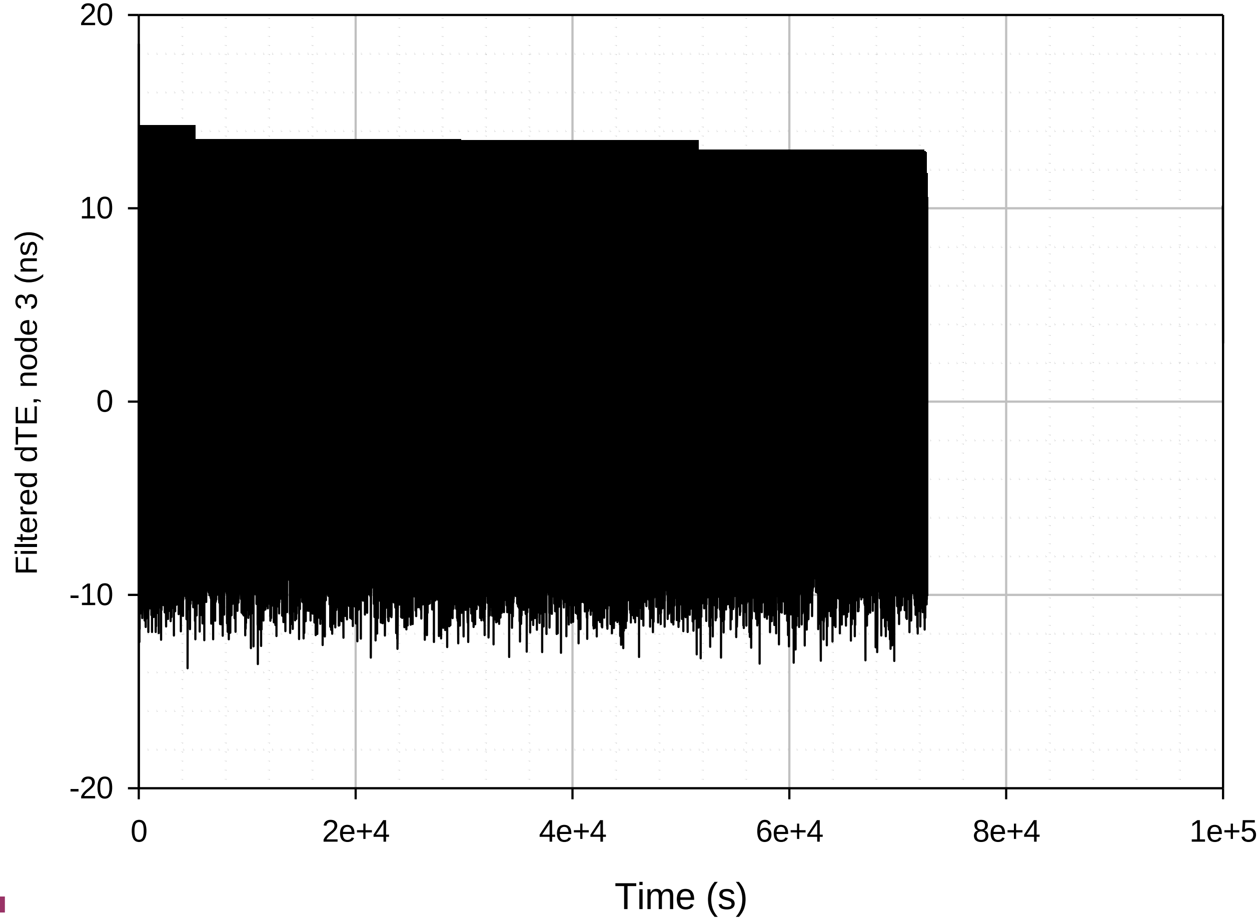
Case 1, Replication 1
rateRatio field of transmitted Sync message by DUT minus actual rate ratio of DUT working clock relative to Working Clock at GM at transmission of Sync message
Node 3



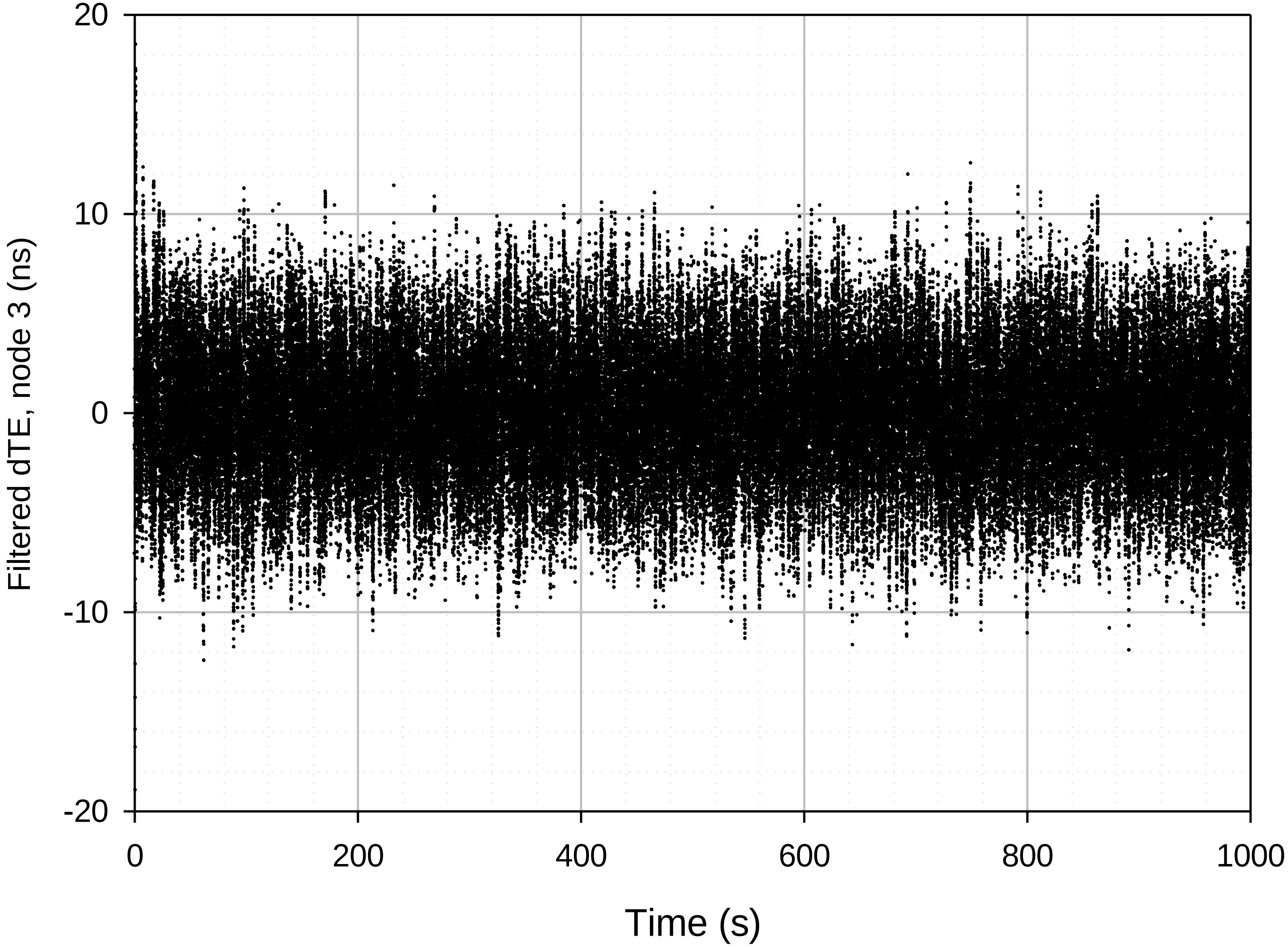
Case 1, Replication 1
rateRatioDrift field of transmitted Sync message by DUT minus actual rate ratio drift rate of DUT working clock relative to Working Clock at GM at transmission of Sync message
Node 3



Case 1, Replication 1
Filtered dTE (PTP End Instance), Node 3
Detail of 2 - 100000 s
Min and Max of each block of 5000 data points is plotted,
and successive points are joined with a line

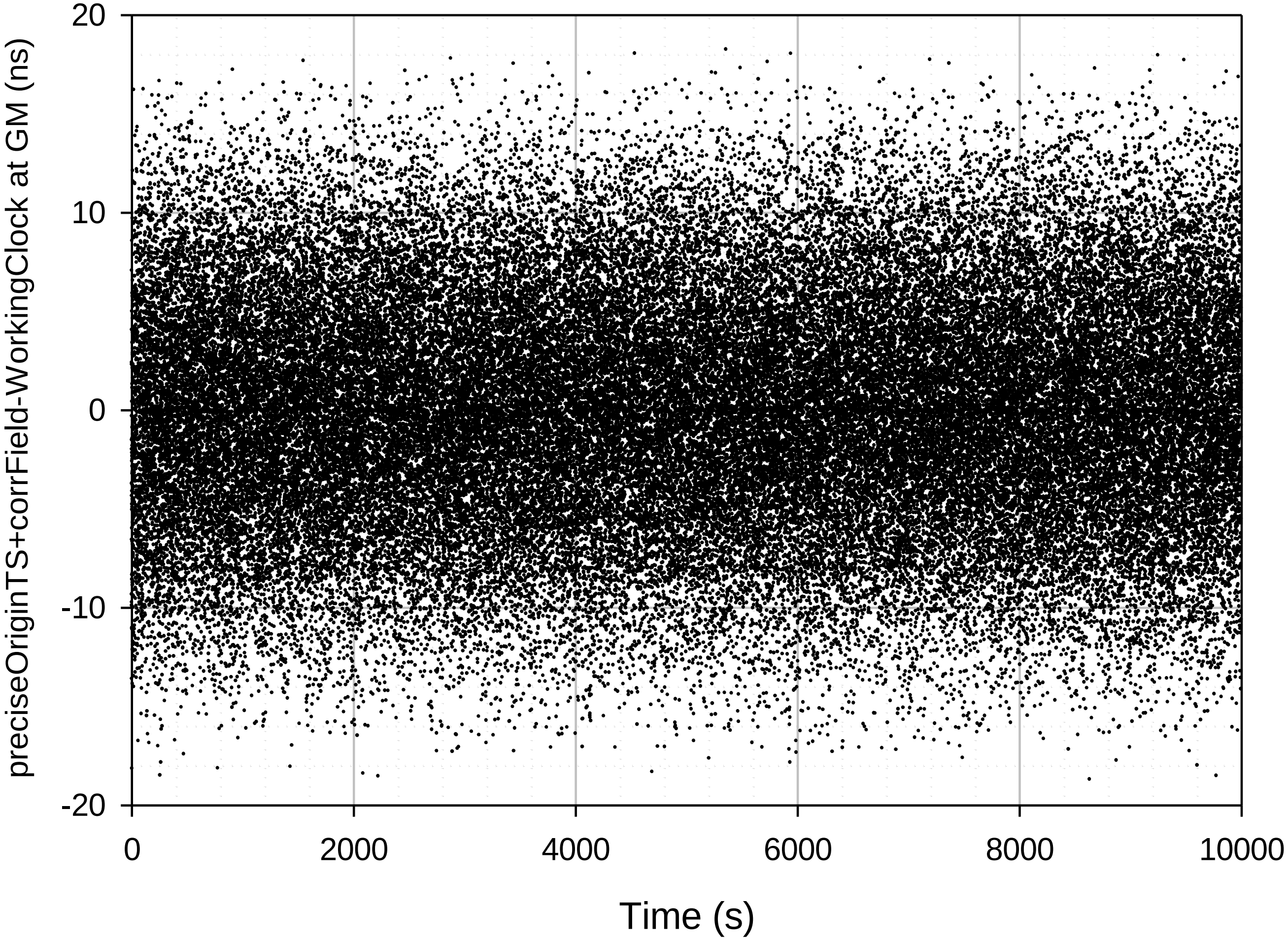


Case 1, Replication 1
Filtered dTE (PTP End Instance), Node 3
Detail of 2 - 1000 s

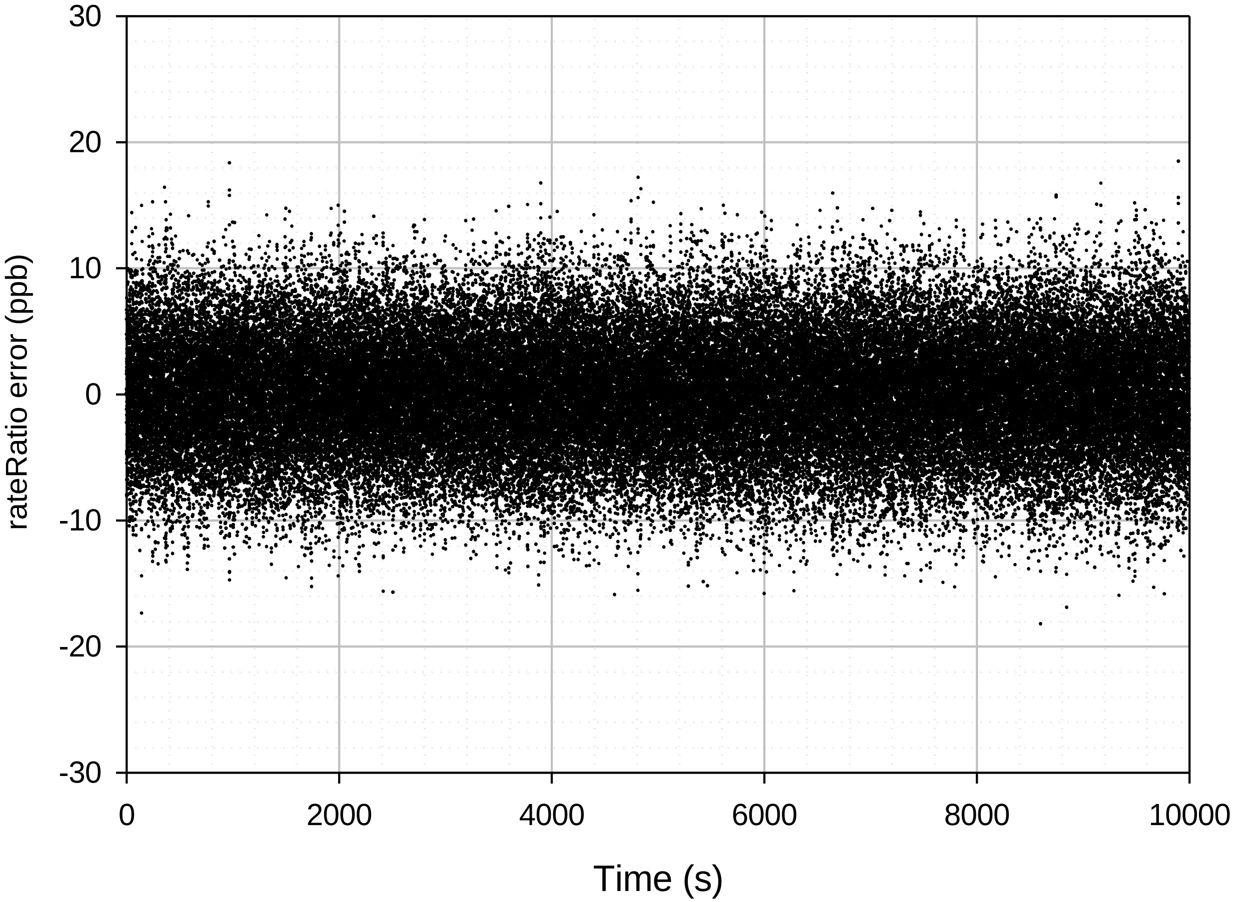


Plots for Case 1b – following 4 slides

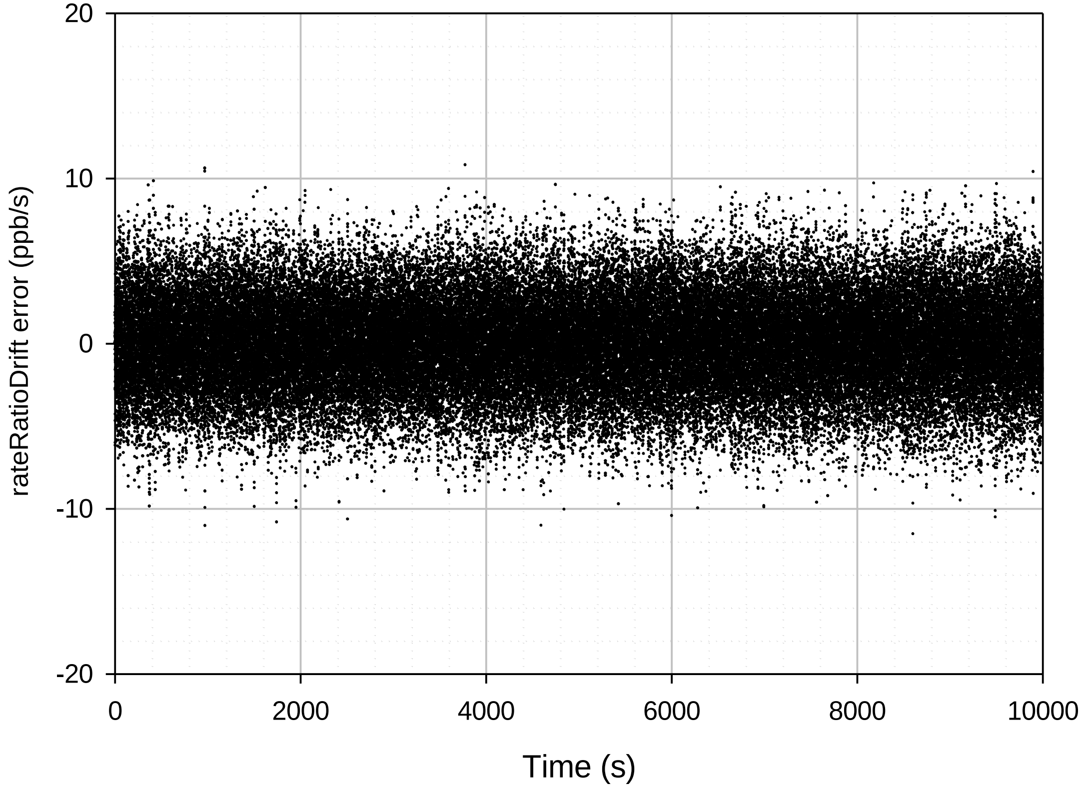
Case 1b, Replication 1
preciseOriginTimestamp + correctionField - Working Clock at GM at transmission of Sync message
Node 3



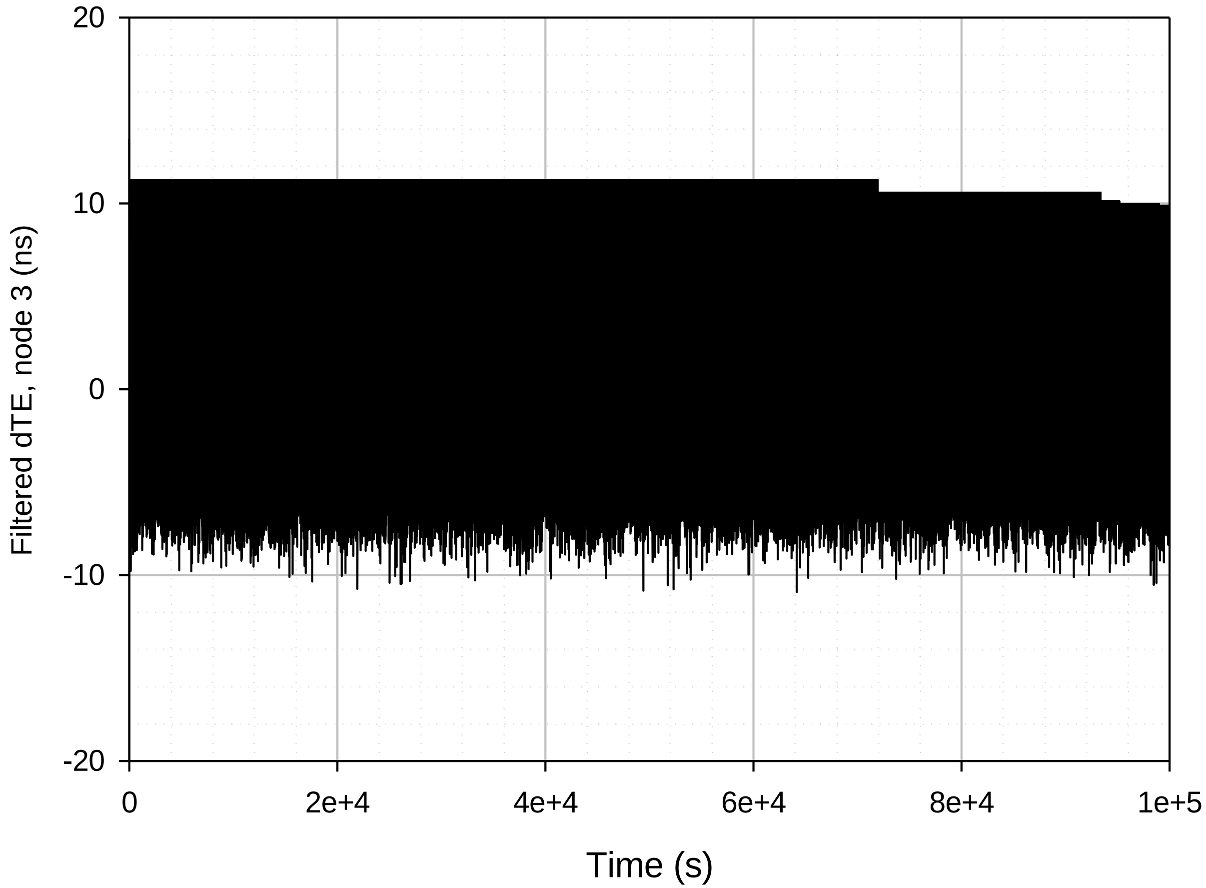
Case 1b, Replication 1
rateRatio field of transmitted Sync message by DUT minus actual rate ratio of DUT working clock relative to Working Clock at GM at transmission of Sync message
Node 3



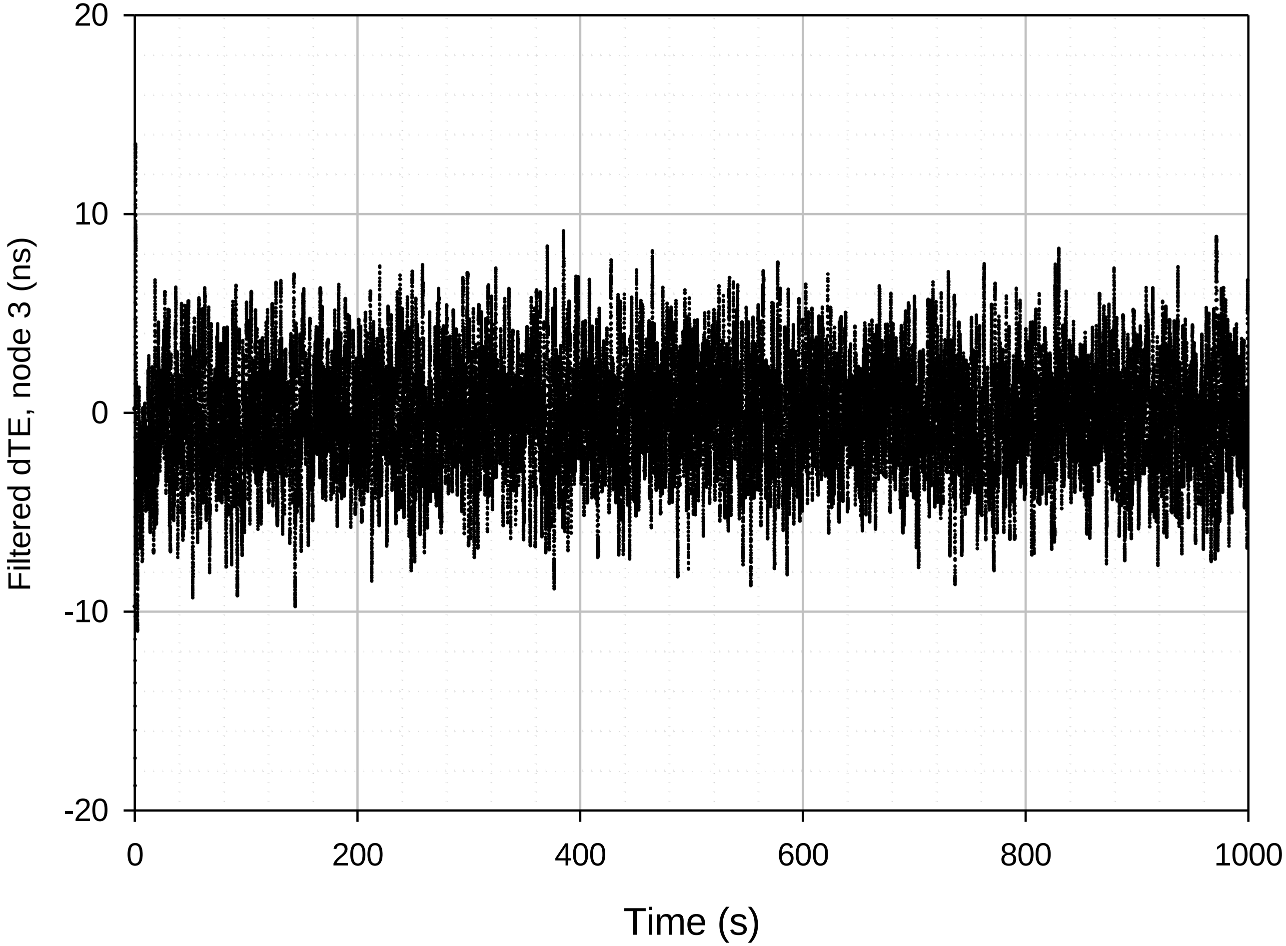
Case 1b, Replication 1
rateRatioDrift field of transmitted Sync message by DUT minus actual rate ratio drift rate of DUT working clock relative to Working Clock at GM at transmission of Sync message
Node 3



Case 1b, Replication 1
Filtered dTE (PTP End Instance), Node 3
Detail of 2 - 100000 s
Min and Max of each block of 5000 data points is plotted, and successive points are joined with a line

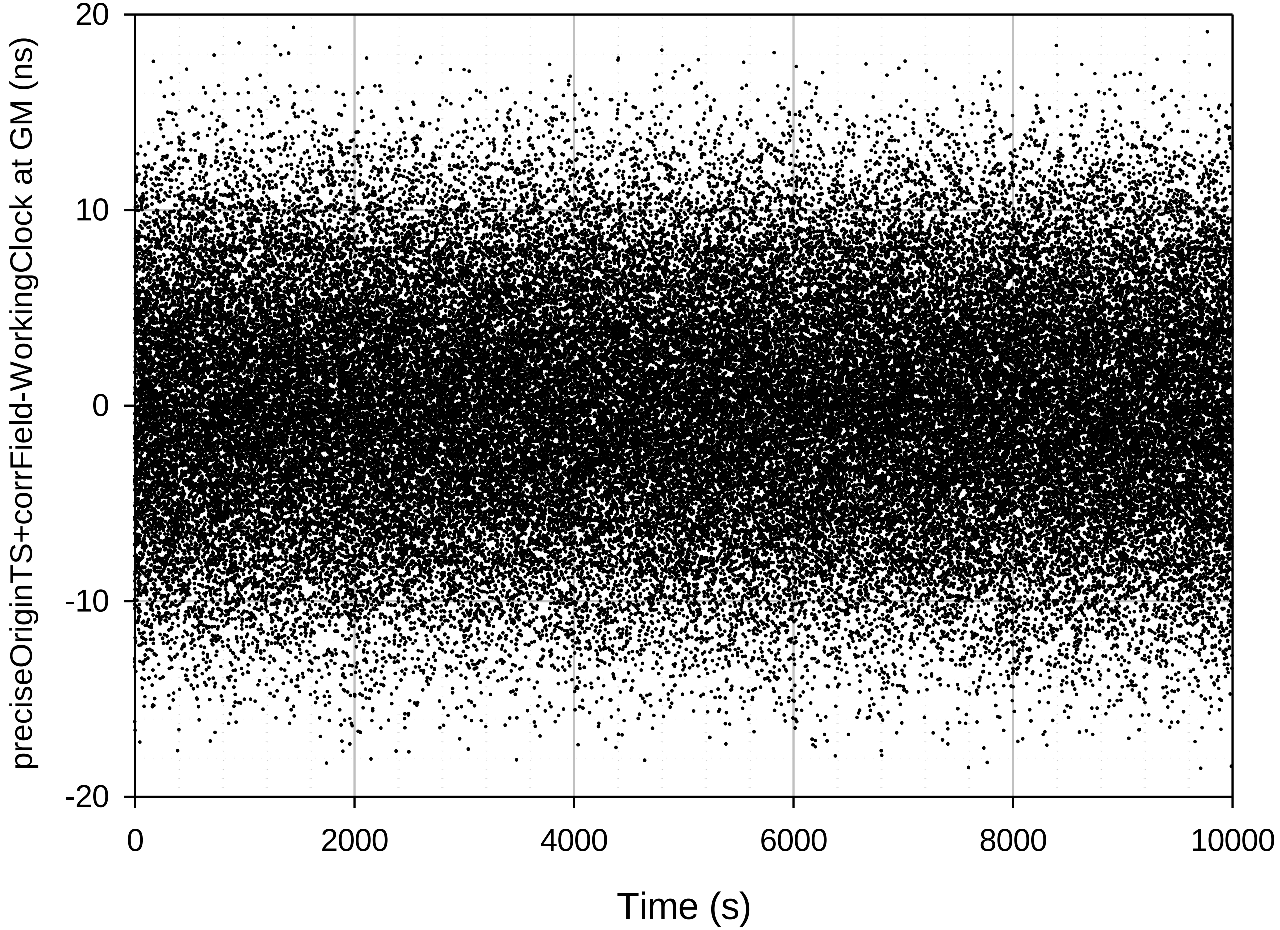


Case 1b, Replication 1
Filtered dTE (PTP End Instance), Node 3
Detail of 2 - 1000 s

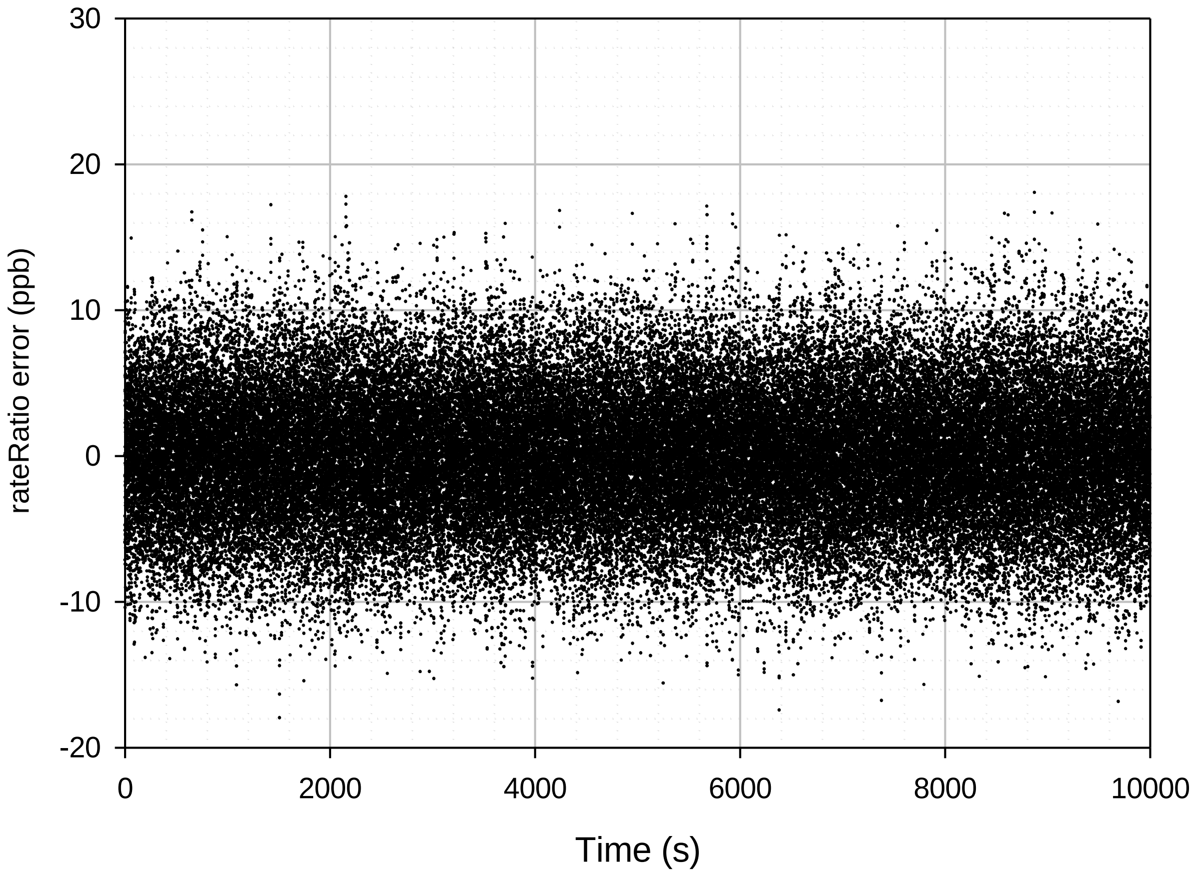


Plots for Case 1c - following 4 slides

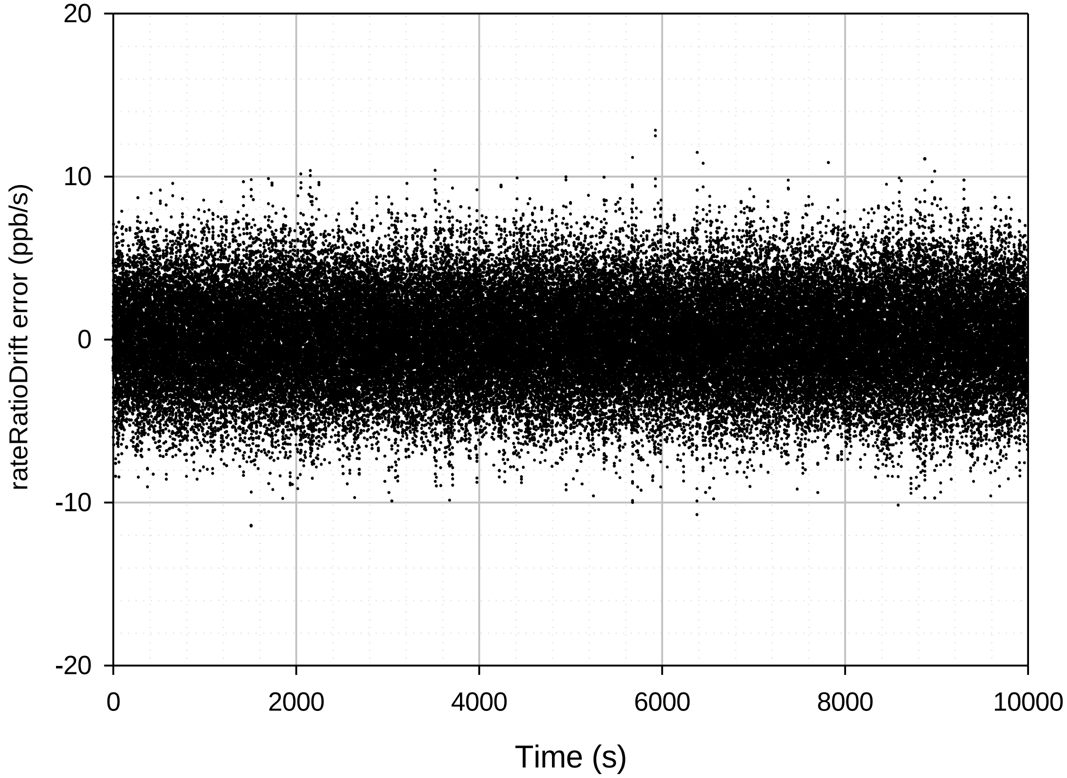
Case 1c, Replication 1
preciseOriginTimestamp + correctionField - Working Clock at GM at transmission of Sync message
Node 3



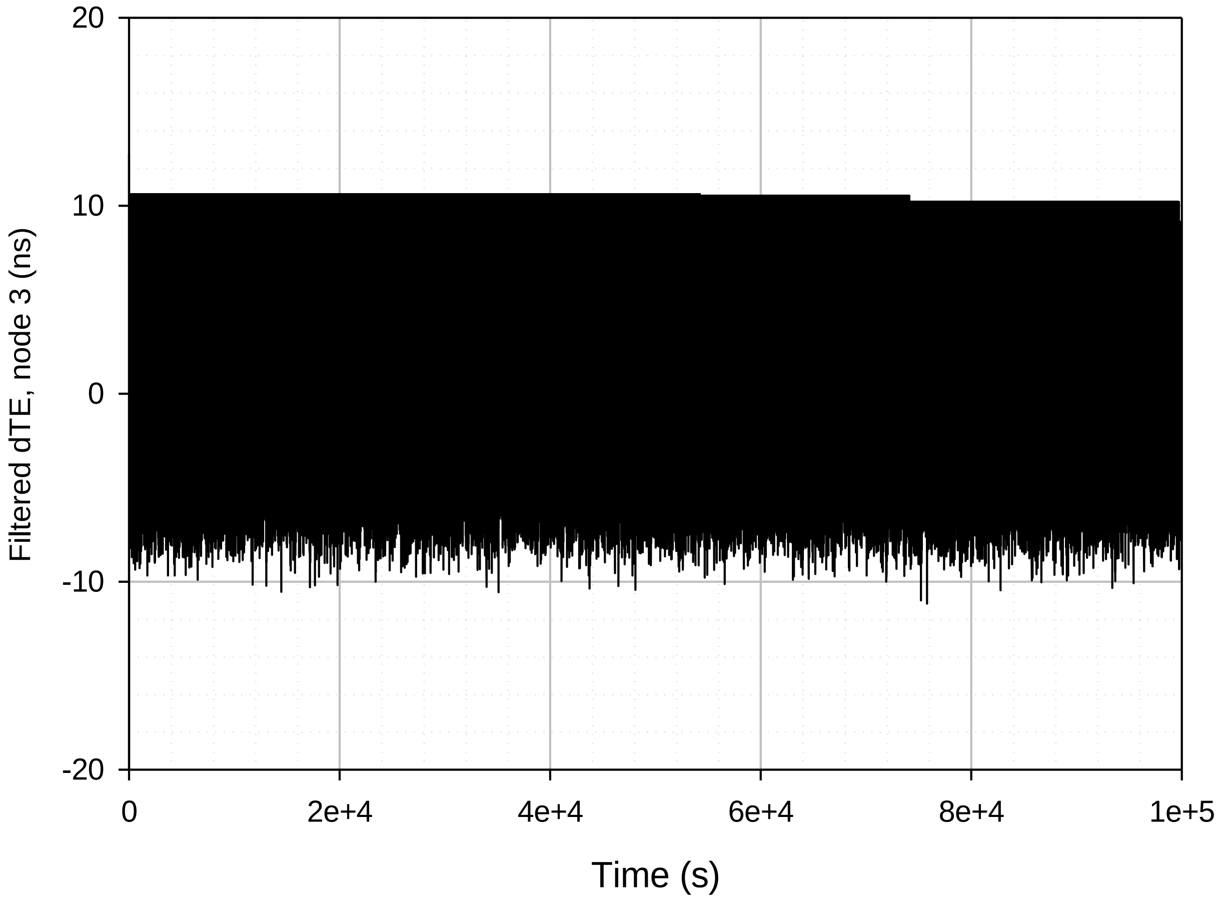
Case 1c, Replication 1
rateRatio field of transmitted Sync message by DUT minus actual rate ratio of DUT working clock relative to Working Clock at GM at transmission of Sync message
Node 3



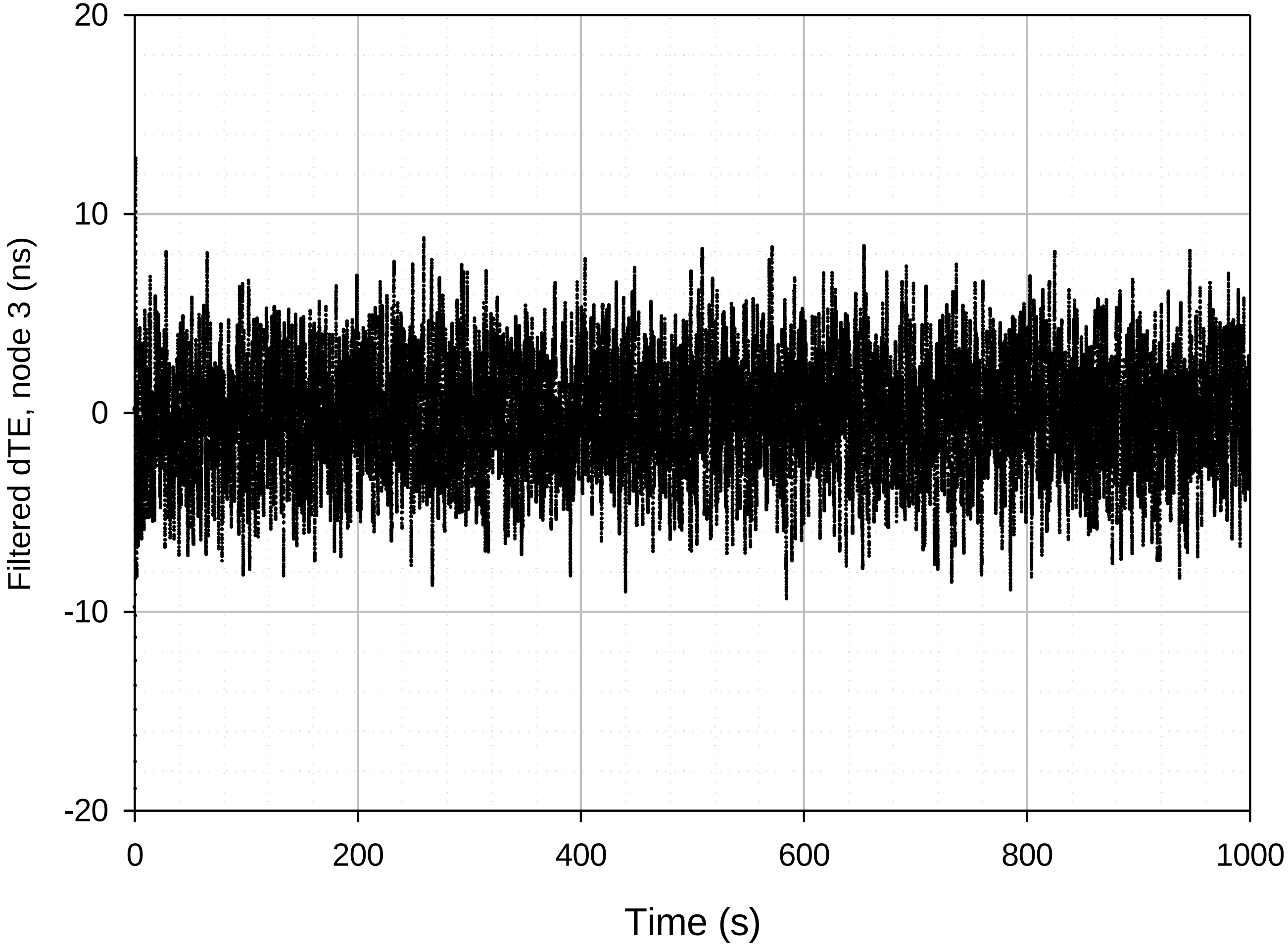
Case 1c, Replication 1
rateRatioDrift field of transmitted Sync message by DUT minus actual rate ratio drift rate of DUT working clock relative to Working Clock at GM at transmission of Sync message
Node 3



Case 1c, Replication 1
Filtered dTE (PTP End Instance), Node 3
Detail of 2 - 100000 s
Min and Max of each block of 5000 data points is plotted, and successive points are joined with a line



Case 1c, Replication 1
Filtered dTE (PTP End Instance), Node 3
Detail of 2 - 1000 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	453.862	453.862	453.855	454.040	453.858	454.032
5^{th} percentile over time	454.036	454.122	454.038	454.135	454.044	454.127
95^{th} percentile over time	454.288	454.392	454.288	454.387	454.294	454.389
Maximum over time	454.375	454.557	454.375	454.532	454.389	454.575
Mean over time	454.179	454.248	454.182	454.245	454.178	454.245
Standard Deviation over time	0.059	0.094	0.059	0.098	0.059	0.093

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	-17.940 ($\pm$20 ns)	-16.871 ($\pm$20 ns)	-19.091	-16.451	-19.355	-16.195
5th percentile over time	-8.835 ($\pm$10 ns)	-8.545 ($\pm$10 ns)	-8.047	-7.797	-8.053	-7.839
95th percentile over time	8.560 ($\pm$10 ns)	8.820 ($\pm$10 ns)	7.792	8.067	7.809	8.032
Maximum over time	16.881 ($\pm$20 ns)	18.052 ($\pm$20 ns)	15.768	19.187	16.353	19.396
Mean over time	-0.079	0.067	-0.077	0.074	-0.079	0.075
Standard Deviation over time	5.214	5.295	4.782	4.854	4.768	4.851

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	-17.937 (±20 ns)	-16.876 (±20 ns)	-19.123	-16.426	-19.319	-16.170
5th percentile over time	-8.793 (±10 ns)	-8.579 (±10 ns)	-8.034	-7.849	-8.022	-7.856
95th percentile over time	8.594 (±10 ns)	8.818 (±10 ns)	7.826	8.025	7.829	8.016
Maximum over time	16.837 (±20 ns)	18.091 (±20 ns)	15.740	19.180	16.325	19.397
Mean over time	-1.973	2.008	-0.077	0.074	-0.079	0.075
Standard Deviation over time	3.990	4.449	4.782	4.854	4.768	4.851

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	-21.750	-15.435	-21.977	-15.566	-21.243	-15.162
5^{th} percentile over time	-7.273	-6.991	-7.295	-6.991	-7.272	-6.997
95^{th} percentile over time	6.994	7.286	6.983	7.316	6.978	7.297
Maximum over time	16.019	22.727	15.703	21.012	15.706	22.214
Mean over time	-2.907×10^{-3} ($\pm$100 ppb)	1.903×10^{-3} ($\pm$100 ppb)	-9.422×10^{-3}	2.736×10^{-3}	-1.599×10^{-3}	1.824×10^{-3}
Standard Deviation over time	4.259 ($\pm$20 ppb)	4.406 ($\pm$20 ppb)	4.263	4.416	4.245	4.411

Experiment 1, 1b, and 1c Results

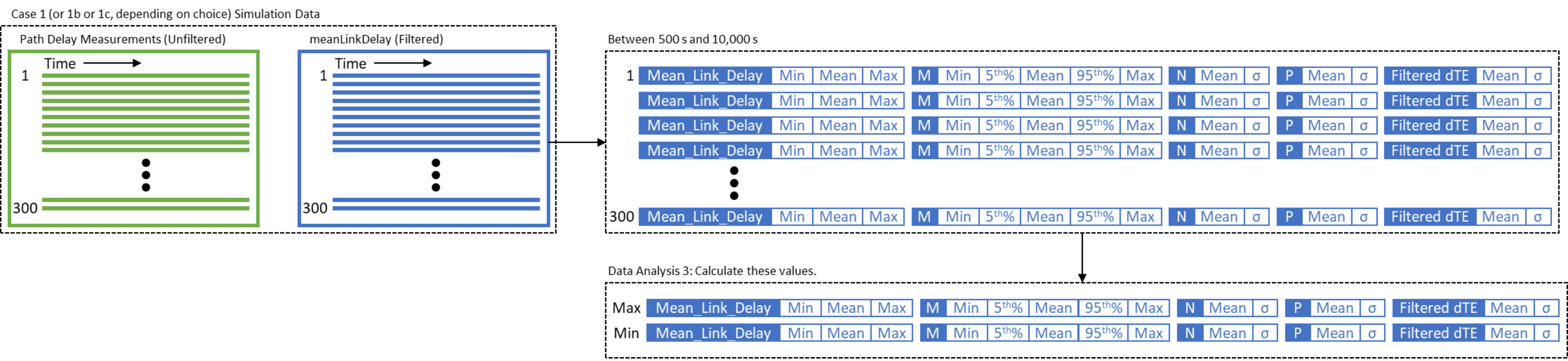
rateRatioDrift field of Sync minus actual rate ratio drift, when Sync is sent (i.e., P) (ppb/s)						
	Case 1		Case 1b		Case 1c	
Statistic computed over time	**Minimum over 300 replics**	**Maximum over 300 replics**	**Minimum over 300 replics**	**Maximum over 300 replics**	**Minimum over 300 replics**	**Maximum over 300 replics**
Minimum over time	-14.060	-9.737	-14.063	-9.930	-13.534	-9.700
5th percentile over time	-4.533	-4.306	-4.511	-4.317	-4.513	-4.301
95th percentile over time	4.311	4.545	4.328	4.515	4.319	4.547
Maximum over time	9.233	13.983	9.783	13.347	9.546	13.768
Mean over time	-1.970×10^{-3} ($\pm$100 ppb/s)	9.736×10^{-4} ($\pm$100 ppb/s)	-1.149E-03	1.050E-03	-9.536E-04	1.393E-03
Standard Deviation over time	2.633 ($\pm$20 ppb/s)	2.737 ($\pm$20 ppb/s)	2.641	2.743	2.627	2.741

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	-14.981 (±15)	-12.084 (±15)	-12.016	-9.537	-12.394	-9.495
5^{th} percentile over time	-5.46 (±15)	-5.331 (±15)	-4.494	-4.321	-4.506	-4.308
95^{th} percentile over time	5.342 (±15)	5.473 (±15)	4.324	4.516	4.325	4.494
Maximum over time	12.276 (±15)	15.327 (±15)	9.432	12.316	9.563	12.324
Mean over time	-0.062 (±15)	0.066 (±15)	-0.051	0.044	-0.053	0.047
Standard Deviation over time	3.247	3.306	2.644	2.717	2.639	2.715

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])

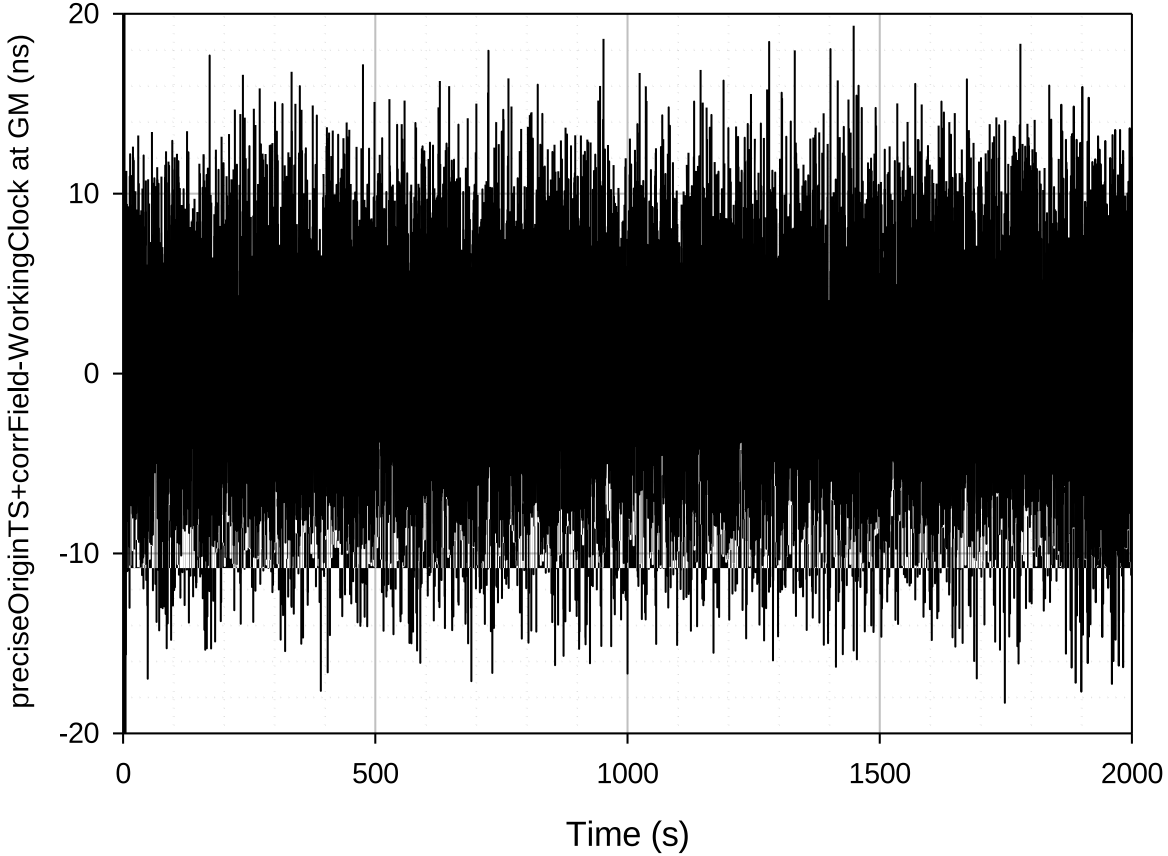


Experiments 2, 3, and 4 Data Analysis - 2

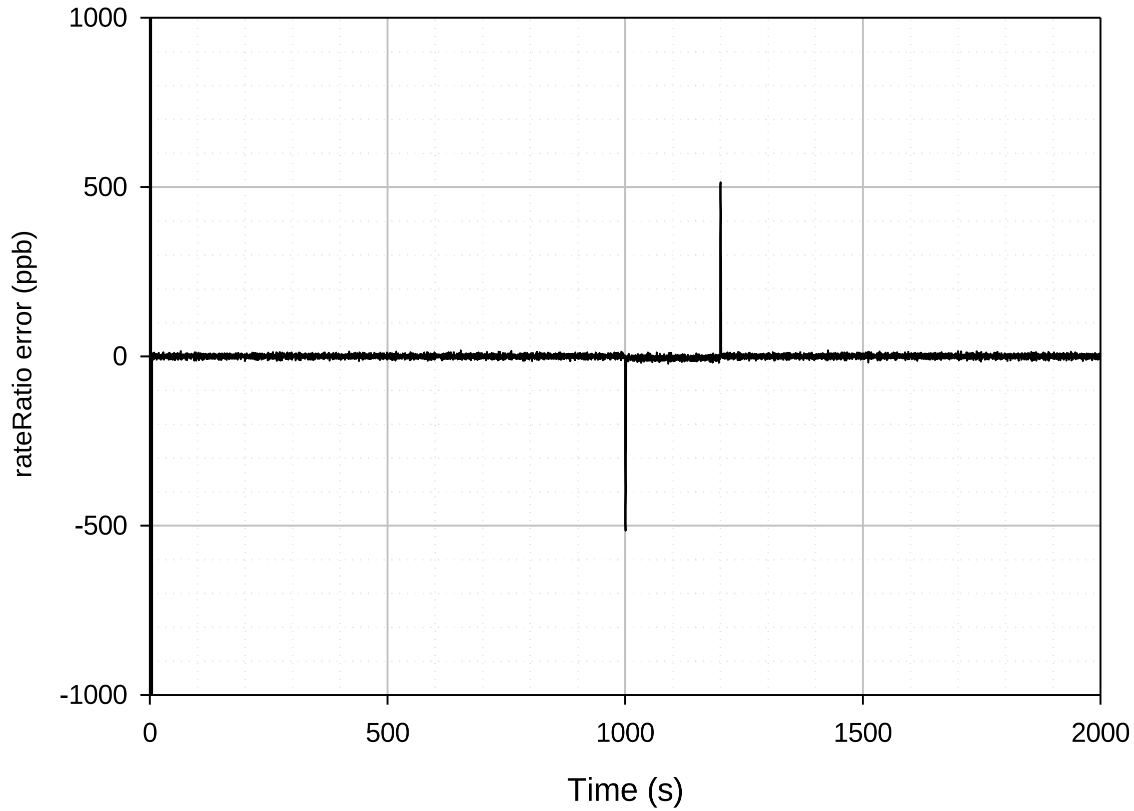
- The following plots are generated for Replication 1, for each of cases 2 and 3 (in some cases, 2 plots are given for the same result, one that shows overall behavior including transients when clock drift starts and stops, and one that zooms in on detail but does not show transients on the scale of 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

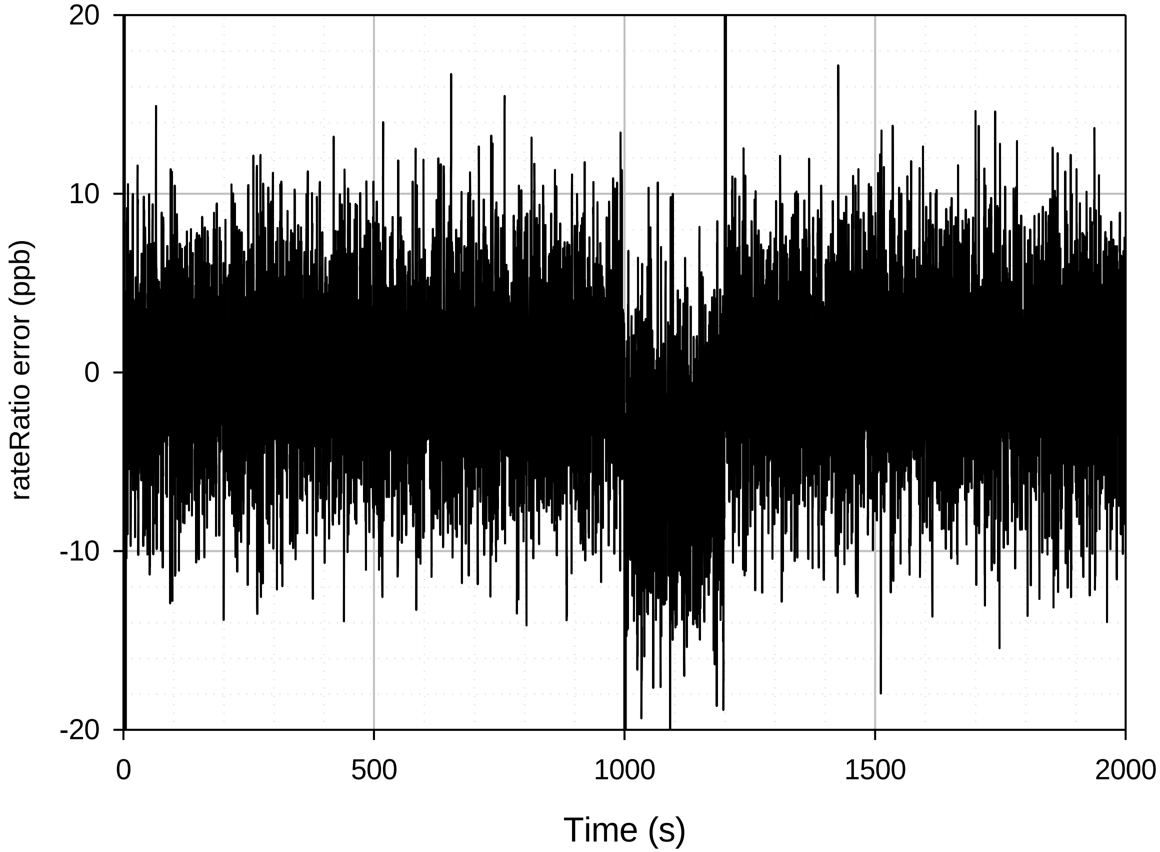
Case 2, Replication 1
preciseOriginTimestamp + correctionField - Working Clock at GM at transmission of Sync message
Detail of initial transient not shown on scale of plot
Successive points are joined with a line
Node 3



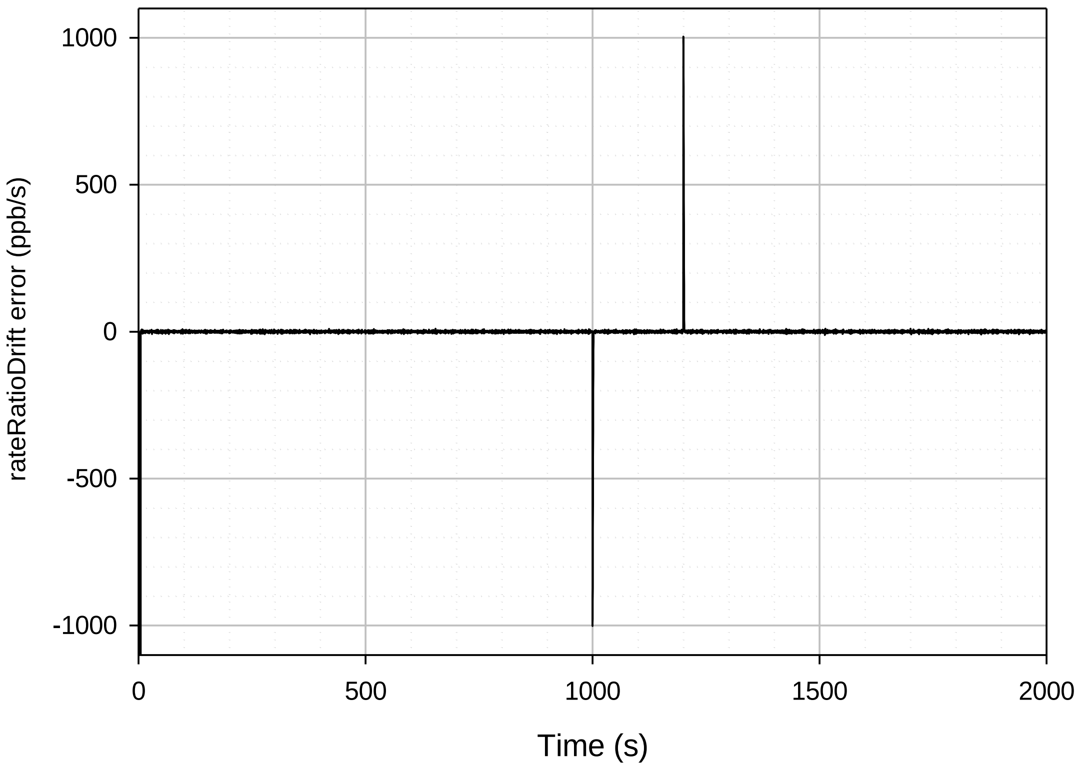
Case 2, Replication 1
rateRatio field of transmitted Sync message by DUT minus actual rate ratio of DUT working clock relative to Working Clock at GM at transmission of Sync message
Detail of initial transient not shown on scale of plot
Successive points are joined with a line
Node 3



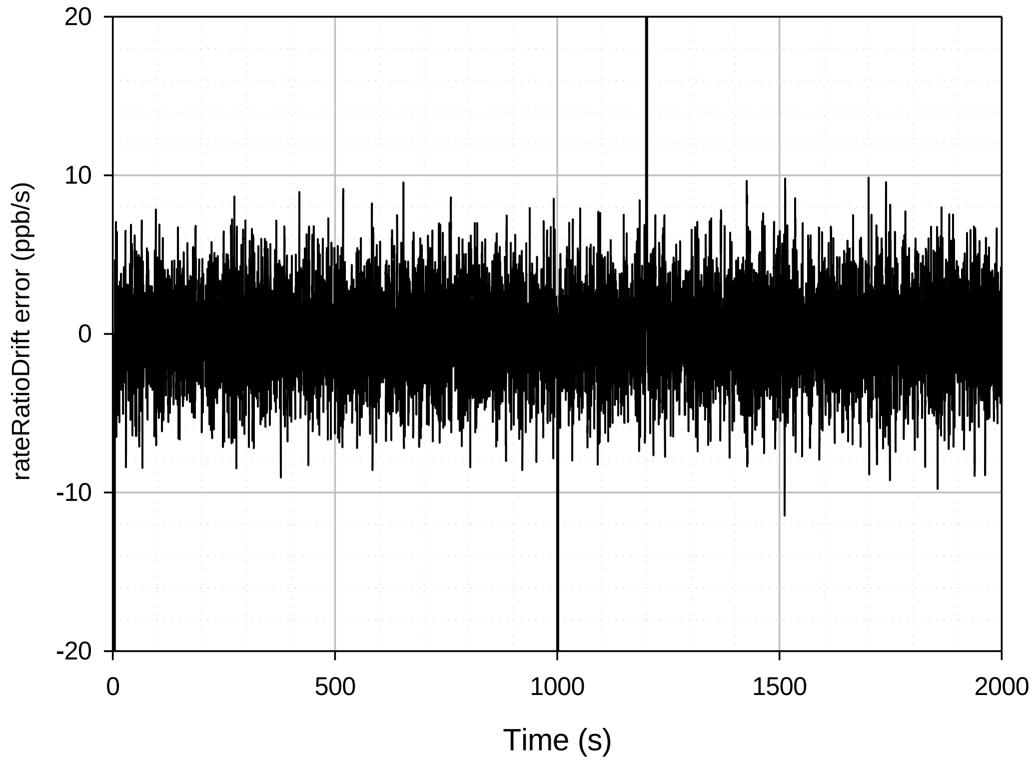
Case 2, Replication 1
rateRatio field of transmitted Sync message by DUT minus actual rate ratio of DUT working clock relative to Working Clock at GM at transmission of Sync message
Detail of initial transient and transients when clock drift starts and stops not shown on scale of plot
Successive points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



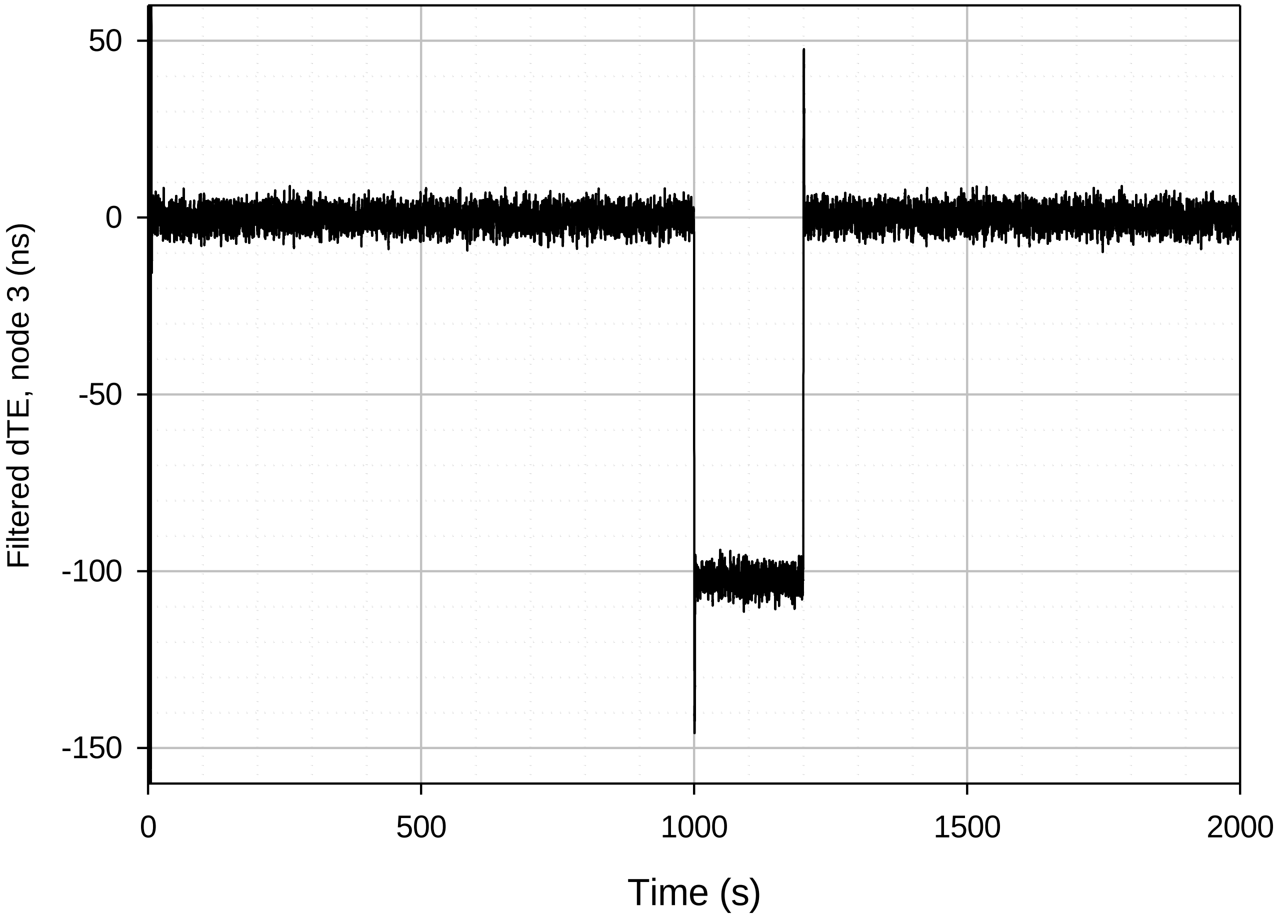
Case 2, Replication 1
rateRatioDrift field of transmitted Sync message by DUT minus actual rate ratio drift rate of DUT working clock relative to Working Clock at GM at transmission of Sync message
Detail of initial transient not shown on scale of plot
Successive points are joined with a line
Node 3



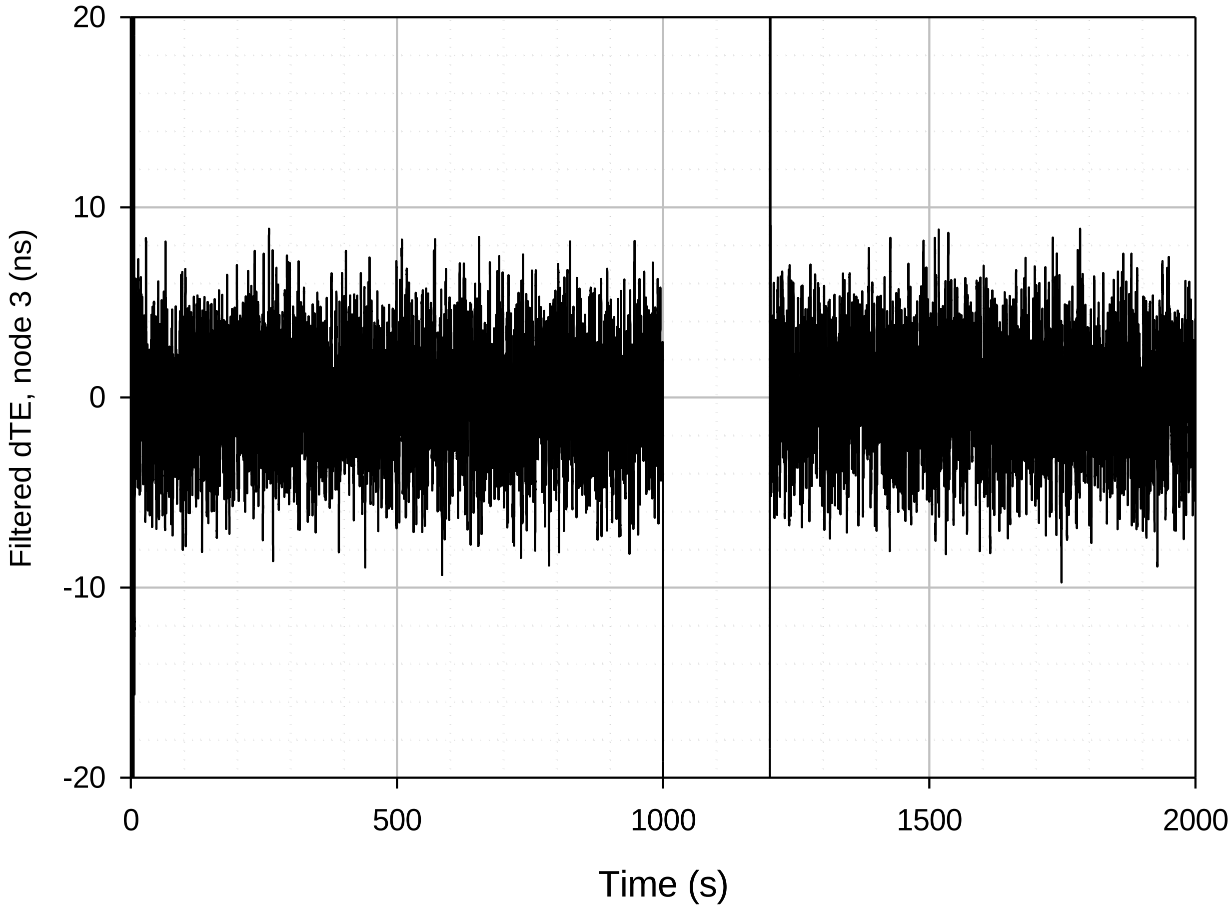
Case 2, Replication 1
rateRatioDrift field of transmitted Sync message by DUT minus actual rate ratio drift rate of DUT working clock relative to Working Clock at GM at transmission of Sync message
Detail of initial transient and transients when clock drift starts and stops not shown on scale of plot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



Case 2, Replication 1
Filtered dTE (PTP End Instance), Node 3
Detail of initial transient not shown on scale of plot
Successive points are joined with a line

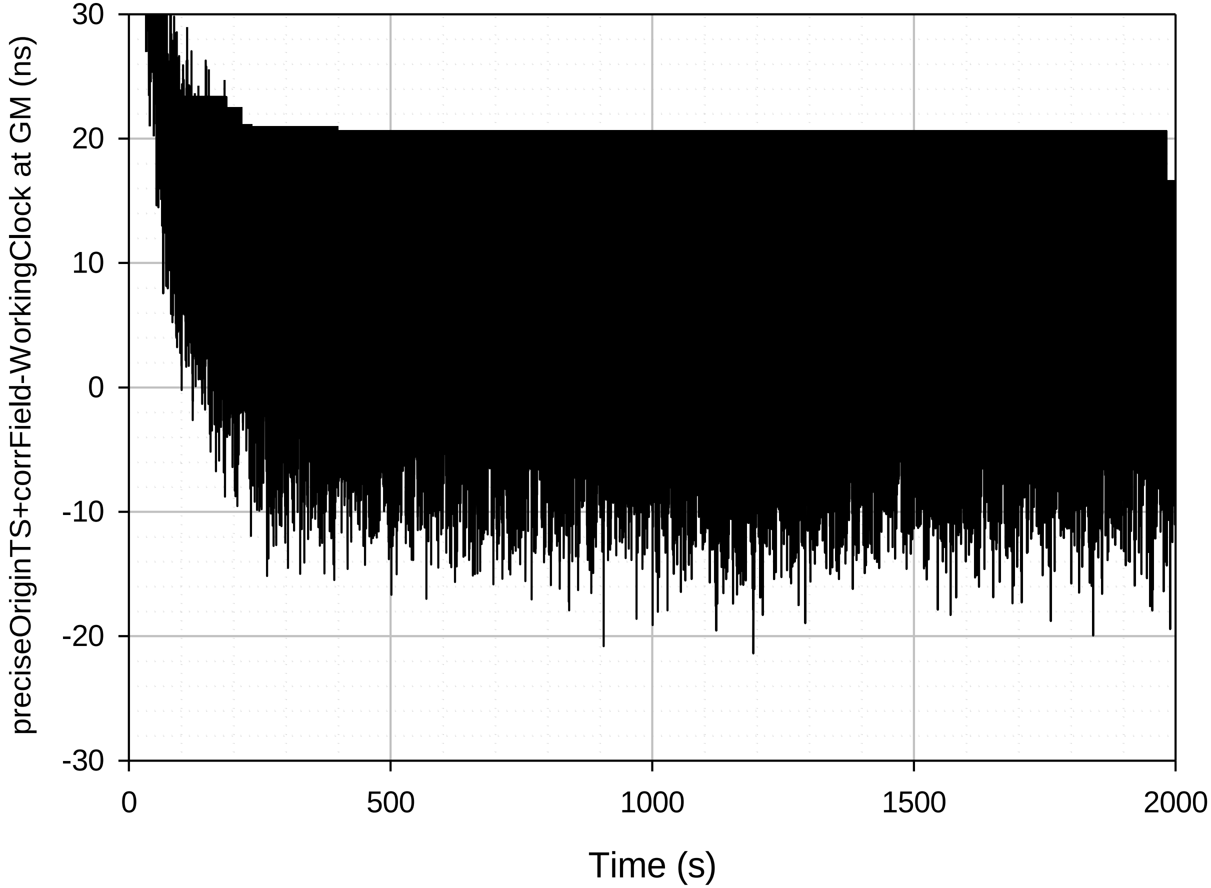


Case 2, Replication 1
Filtered dTE (PTP End Instance), Node 3
Detail of initial transient, period of clock drift, and transients when clock drift starts and stops not shown on scale of plot
Successive points are joined with a line

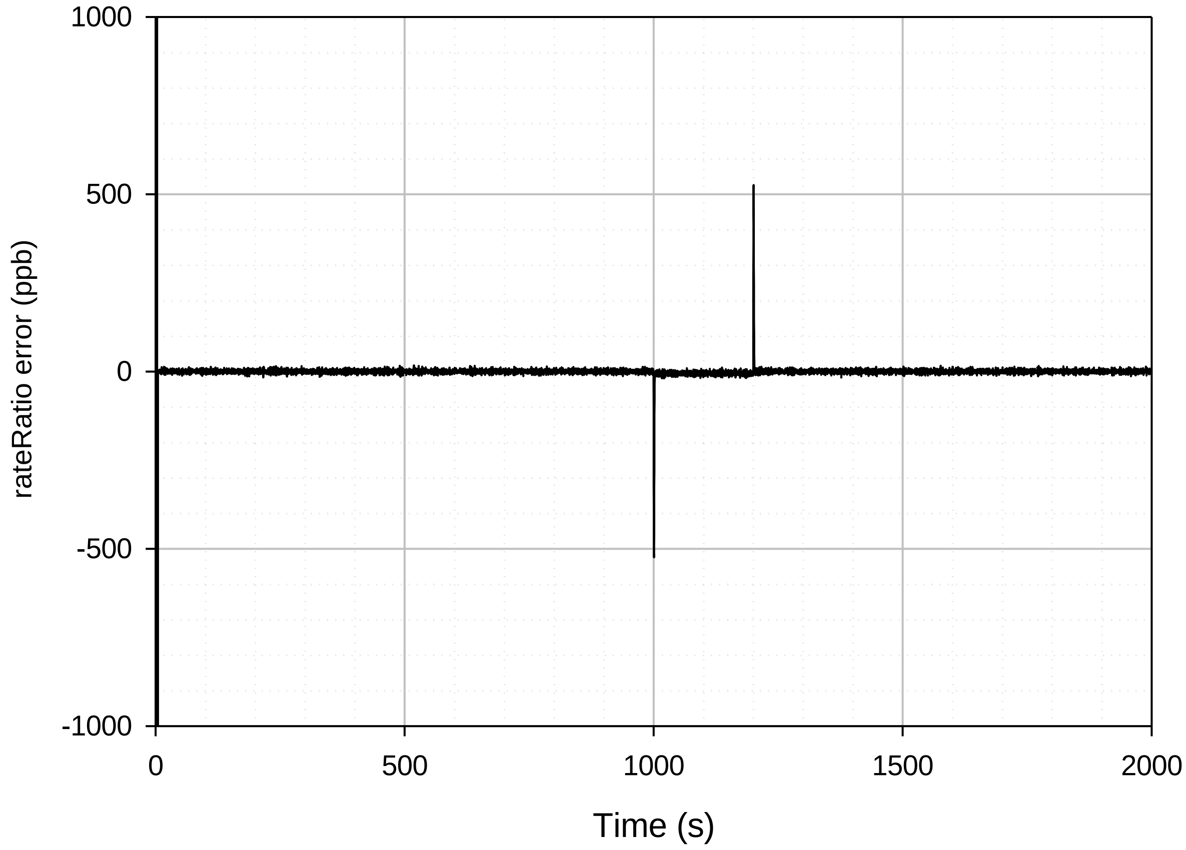


Plots for Case 3 – following 7 slides

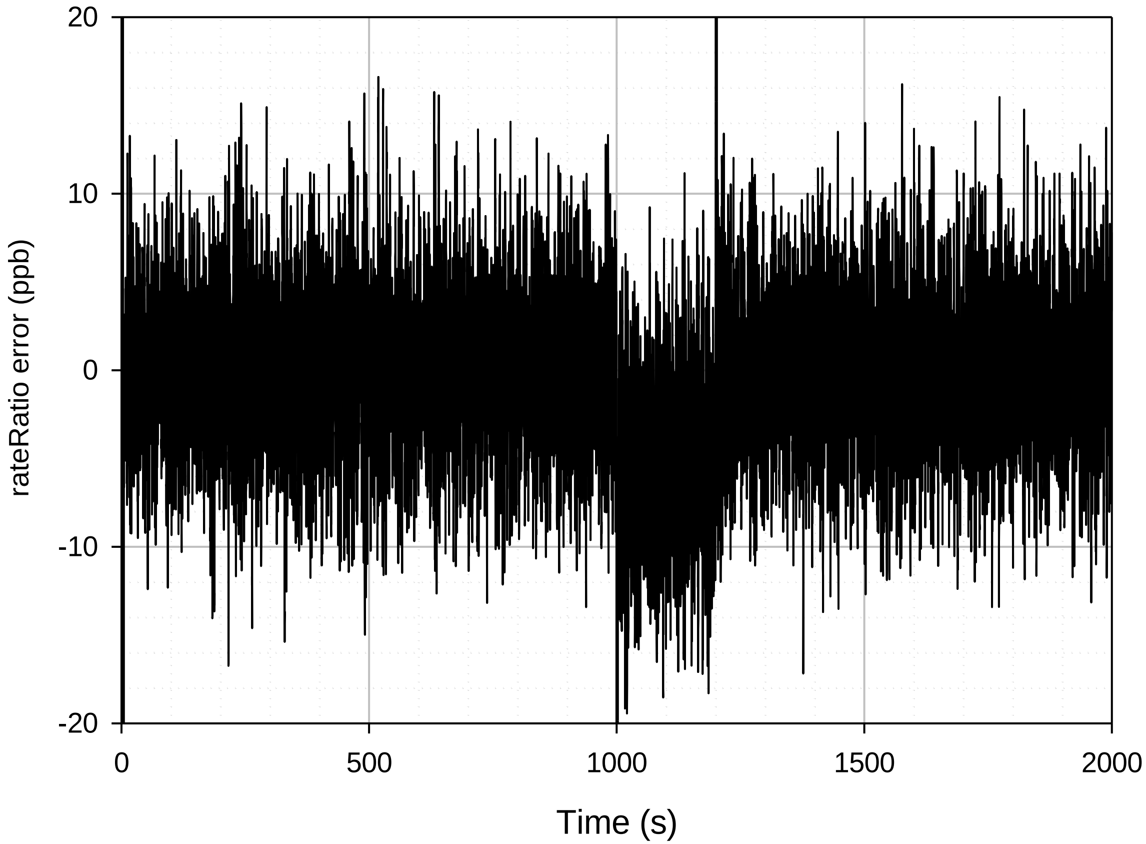
Case 3, Replication 1
preciseOriginTimestamp + correctionField - Working Clock at GM at transmission of Sync message
Full detail of initial transient not shown on scale of plot
Successive points are joined with a line
Node 3



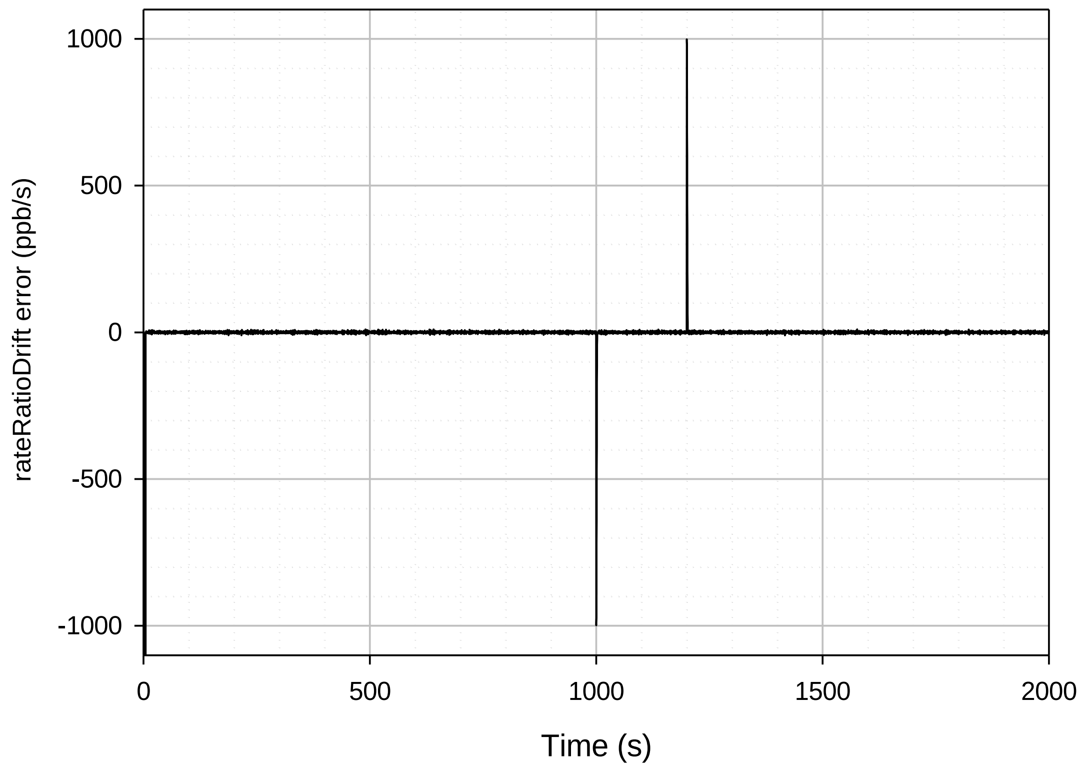
Case 3, Replication 1
rateRatio field of transmitted Sync message by DUT minus actual rate ratio of DUT working clock relative to Working Clock at GM at transmission of Sync message
Detail of initial transient not shown on scale of plot
Successive points are joined with a line
Node 3



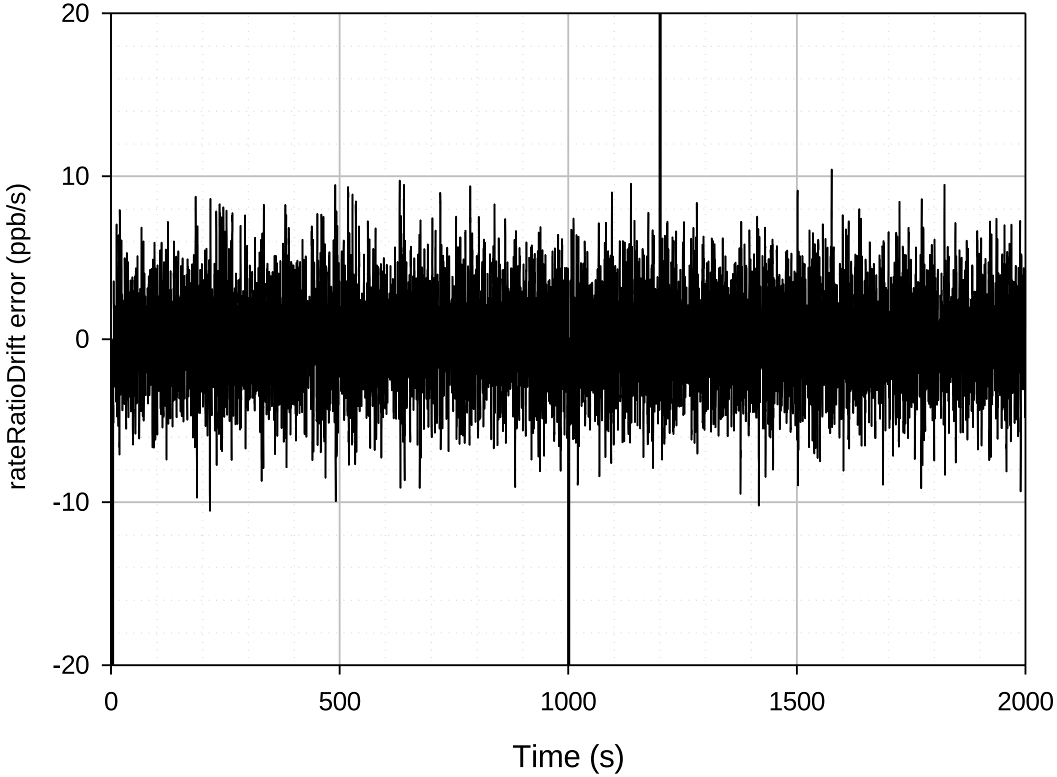
Case 3, Replication 1
rateRatio field of transmitted Sync message by DUT minus actual rate ratio of DUT working clock relative to Working Clock at GM at transmission of Sync message
Detail of initial transient and transients when clock drift starts and stops not shown on scale of plot
Successive points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



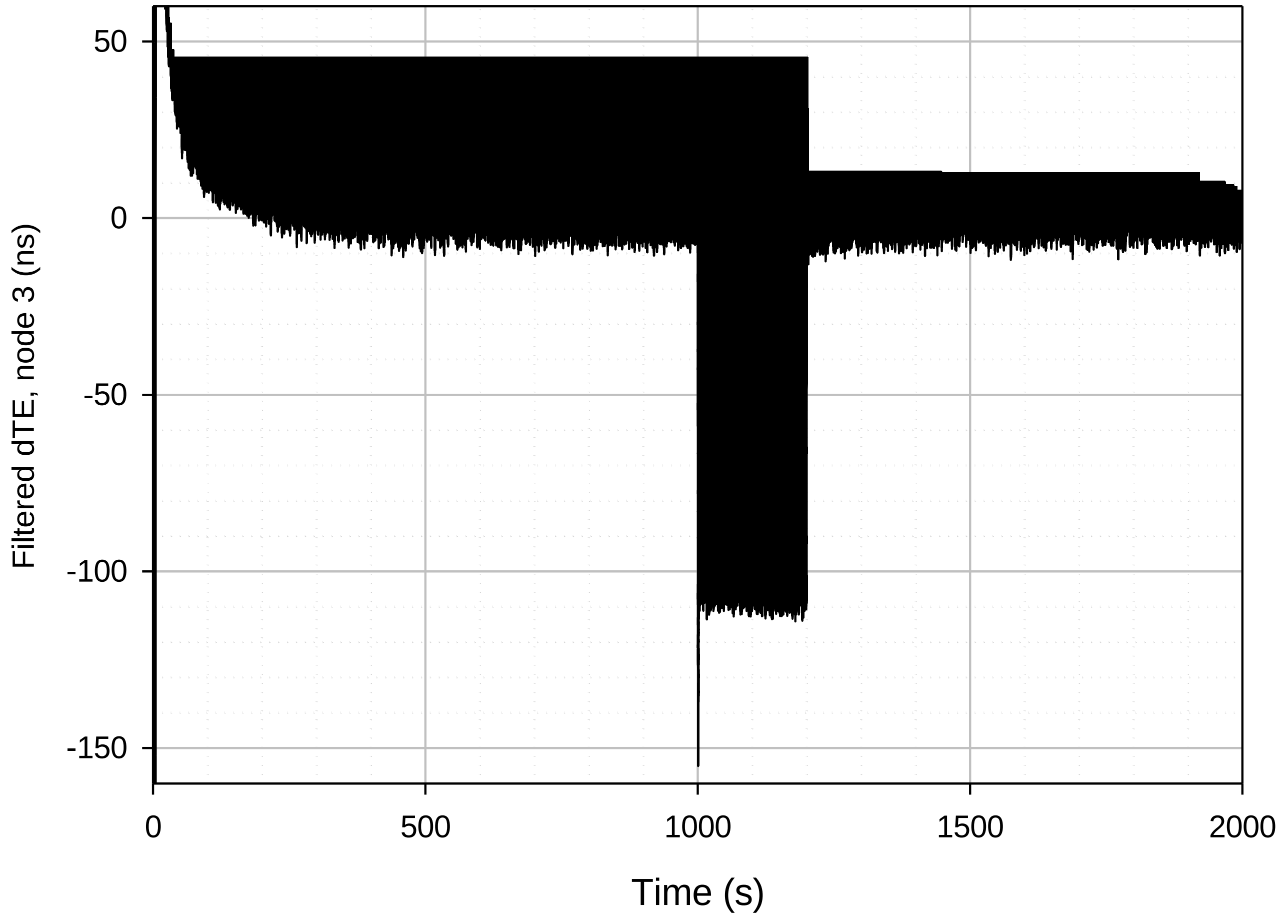
Case 3, Replication 1
rateRatioDrift field of transmitted Sync message by DUT minus actual rate ratio drift rate of DUT working clock relative to Working Clock at GM at transmission of Sync message
Detail of initial transient not shown on scale of plot
Successive points are joined with a line
Node 3



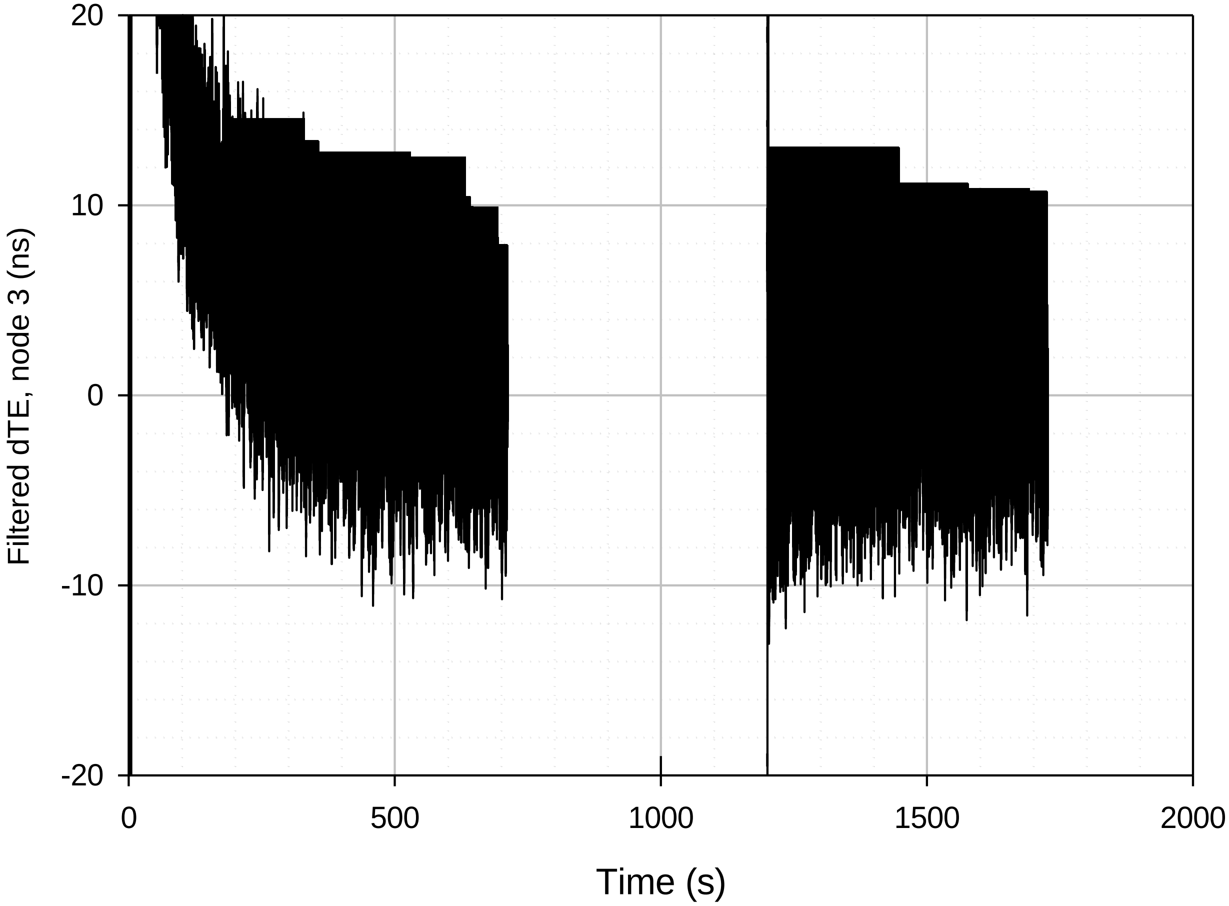
Case 3, Replication 1
rateRatioDrift field of transmitted Sync message by DUT minus actual rate ratio drift rate of DUT working clock relative to Working Clock at GM at transmission of Sync message
Detail of initial transient and transients when clock drift starts and stops not shown on scale of plot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



Case 3, Replication 1
Filtered dTE (PTP End Instance), Node 3
Full detail of initial transient not shown on scale of plot
Successive points are joined with a line

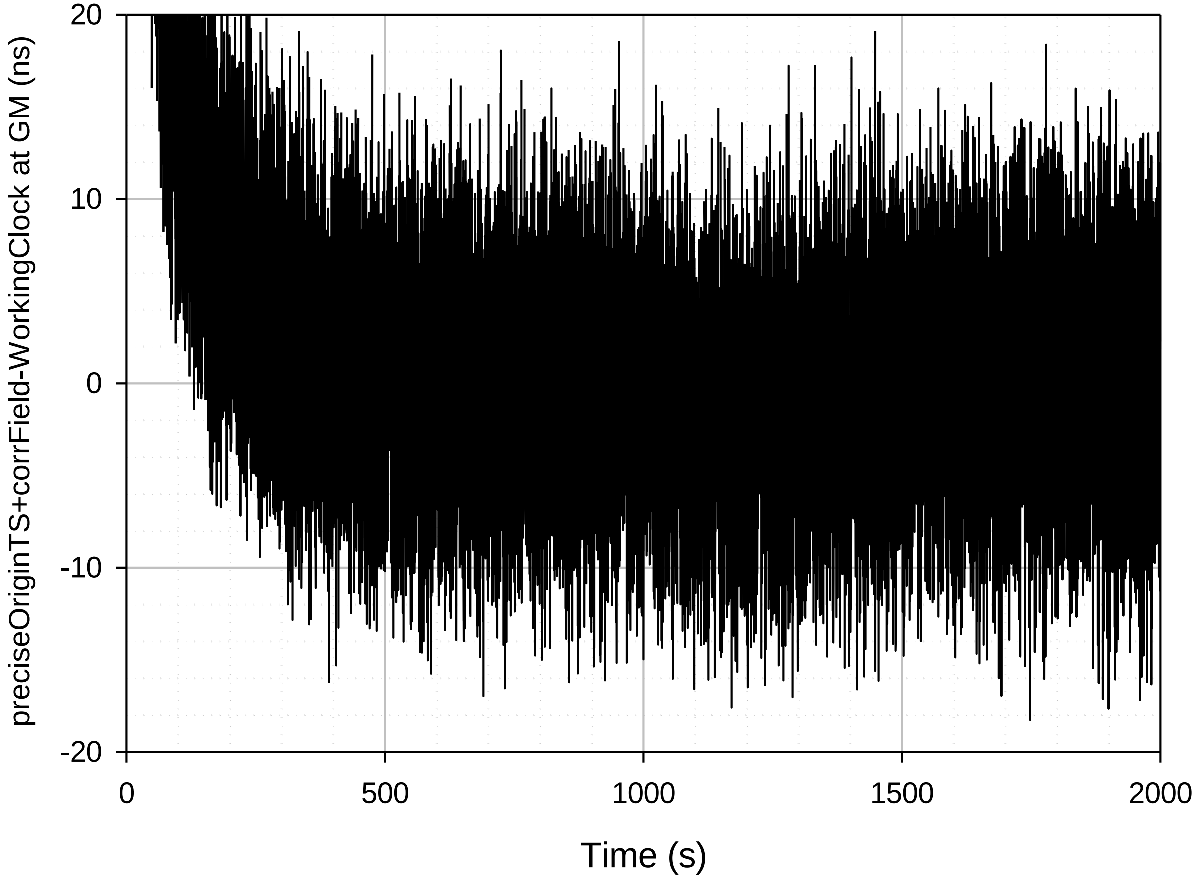


Case 3, Replication 1
Filtered dTE (PTP End Instance), Node 3
Detail of initial transient, period of clock drift, and transients when clock drift starts and stops not shown on scale of plot
Successive points are joined with a line

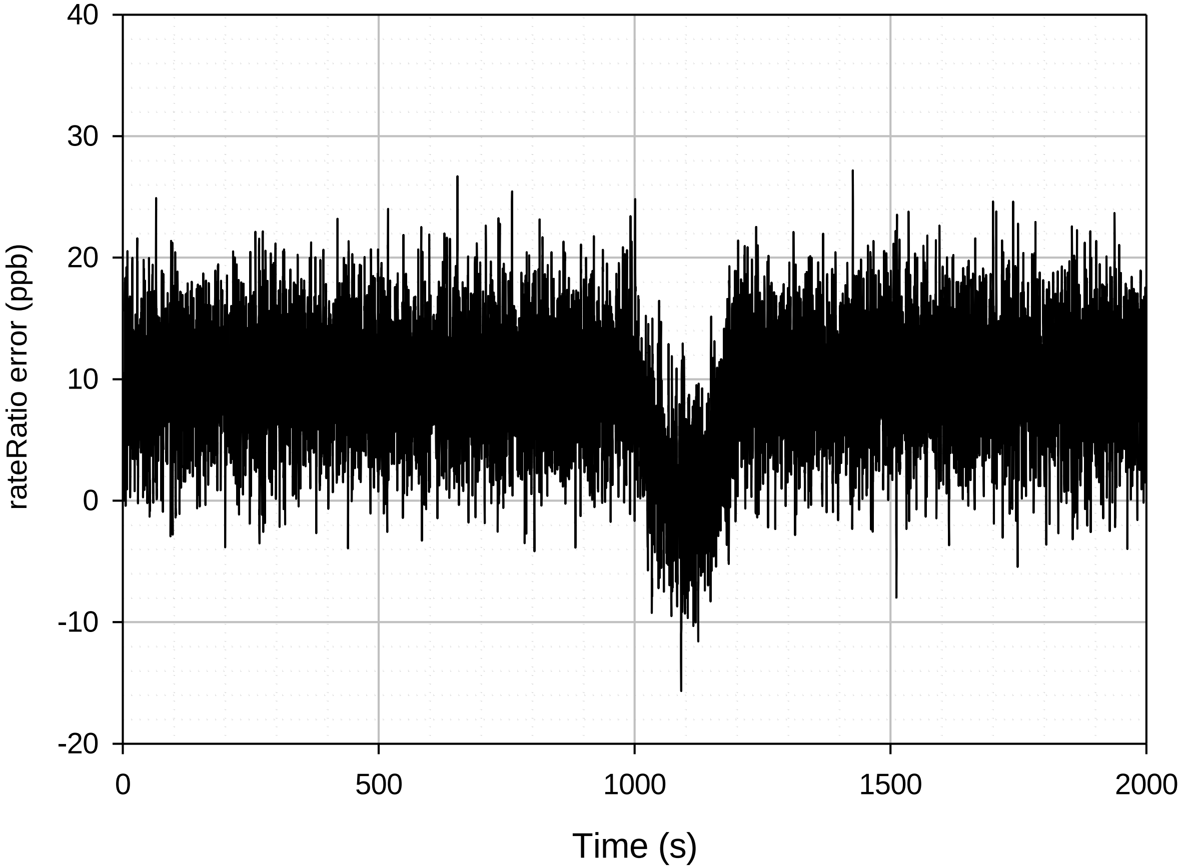


Plots for Case 4 – following 4 slides

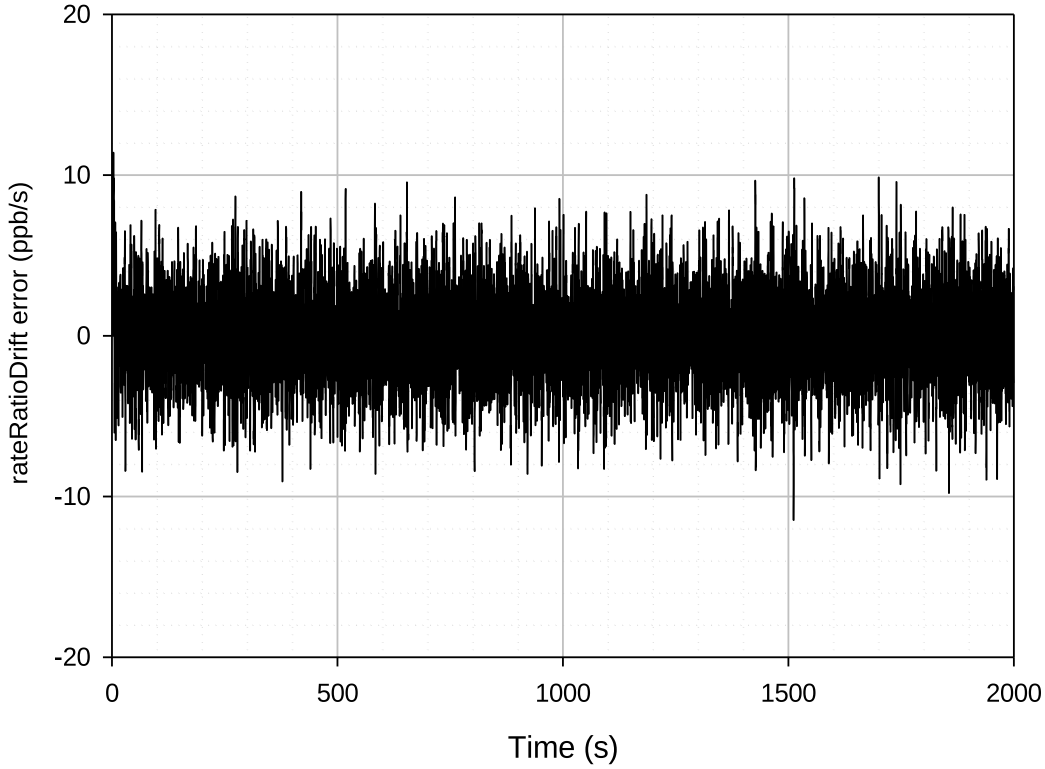
Case 4, Replication 1
preciseOriginTimestamp + correctionField - Working Clock at GM at transmission of Sync message
Full detail of initial transient not shown on scale of plot
Successive points are joined with a line
Node 3



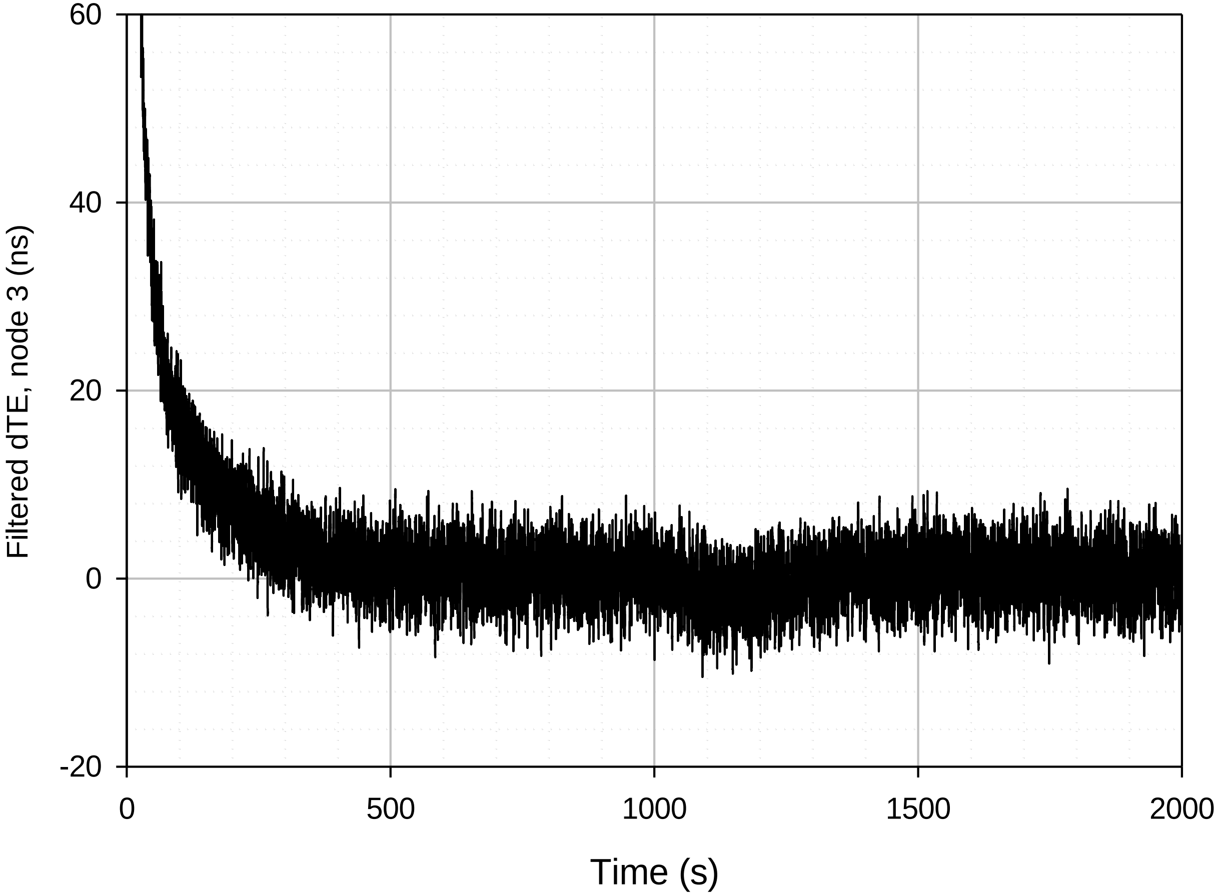
Case 4, Replication 1
rateRatio field of transmitted Sync message by DUT minus actual rate ratio of DUT working clock relative to Working Clock at GM at transmission of Sync message
Detail of initial transient not shown on scale of plot
Successive points are joined with a line
Node 3



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
Successive points are joined with a line
Node 3



Case 4, Replication 1
Filtered dTE (PTP End Instance), Node 3
Full detail of initial transient not shown on scale of plot
Successive points are joined with a line



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	453.898	454.315	451.705	452.338	451.723	452.265
5^{th} percentile over time	453.930	454.328	451.762	452.403	451.755	452.315
95^{th} percentile over time	454.080	454.489	453.649	454.134	453.623	454.096
Maximum over time	454.102	454.522	453.782	454.296	453.850	454.279
Mean over time	454.015	454.399	452.580	452.992	452.571	452.965
Standard Deviation over time	0.016	0.125	0.486	0.705	0.498	0.698

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	-18.370	-11.687	-22.766	-14.664	-20.401	-13.045
5th percentile over time	-8.744	-6.889	-11.083	-9.178	-10.205	-8.643
95th percentile over time	7.067	8.624	6.107	8.065	5.802	7.335
Maximum over time	12.193	18.925	10.993	19.982	10.938	18.049
Mean over time	-0.530	0.548	-2.116	-0.911	-1.899	-0.848
Standard Deviation over time	4.572	5.075	4.891	5.479	4.610	5.129

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	27.645	15.966	-26.973	-15.801	-20.743	-8.775
5^{th} percentile over time	13.994	11.475	-13.568	-11.466	-6.631	-4.008
95^{th} percentile over time	-1.167	-3.791	1.470	3.756	10.908	13.232
Maximum over time	-55.152	-86.513	54.606	90.526	15.546	26.177
Mean over time	5.085 (±100 ppb)	4.800 (±100 ppb)	-5.111 (±100 ppb)	-4.811 (±100 ppb)	3.124	3.225
Standard Deviation over time	-4.422 (±80 ppb)	-5.547 (±80 ppb)	4.465 (±80 ppb)	5.483 (±80 ppb)	4.619	5.736

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	-12.708	-6.272	-13.243	-6.378	-12.643	-6.321
5th percentile over time	-5.309	-3.582	-5.324	-3.729	-5.298	-3.552
95th percentile over time	3.808	5.204	3.633	5.348	3.779	5.177
Maximum over time	579.099	1007.062	575.490	1008.322	6.128	13.001
Mean over time	0.374 (±100 ppb/s)	1.065 (±100 ppb/s)	0.393 (±100 ppb/s)	1.061 (±100 ppb/s)	-0.030	0.041
Standard Deviation over time	15.258 (±80 ppb/s)	30.036 (±80 ppb/s)	15.138 (±80 ppb/s)	30.106 (±80 ppb/s)	2.249	3.134

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	-113.720 [-230, +20]	-109.210 [-230, +20]	-118.250 [-230, +20]	-113.520 [-230, +20]	-12.398	-8.018
5^{th} percentile over time	-107.560 [-230, +20]	-106.320 [-230, +20]	-110.06 [-230, +20]	-108.860 [-230, +20]	-6.479	-5.147
95^{th} percentile over time	-98.760 [-230, +20]	-97.450 [-230, +20]	-98.990 [-230, +20]	-97.890 [-230, +20]	2.534	3.952
Maximum over time	-95.630 [-230, +20]	-91.490 [-230, +20]	-94.240 [-230, +20]	-88.910 [-230, +20]	5.540	10.863
Mean over time	-102.88 [-230, +20]	-102.127 [-230, +20]	-104.360 [-230, +20]	-103.622 [-230, +20]	-1.600	-0.871
Standard Deviation over time	2.341	2.985	3.108	3.534	2.421	3.083

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 $\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 119 are within this range
  - For case 2, the minimum is 453.898 ~~452.004~~ ns and the maximum is ~~454.522~~ ~~456.319~~ ns
  - For case 3, the minimum is 451.705 ~~449.907~~ ns and the maximum is 454.296 ~~454.947~~ ns
  - For case 4, the minimum is 451.723 ~~449.907~~ ns and the maximum is 454.279 ~~454.947~~ ns
  - The ranges for 3 and 4 are almost the same

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 121 (for N), 122 (for P), and 123 (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, P, and filtered dTE 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 101, 109, and 116)
- 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 101, 103, 109, 111, 116, and 117)
  - 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 of [1] are met for cases 2, 3, and 4
  - These requirements are revised in D2.3 of P60802 [1], compared to the previous draft (D2.2)
- 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 104, 105, 112, and 113)
- 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

Experiments 2, 3, and 4 Results - 9

- 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 numerical computations above are for a clock 3dB bandwidth of 1 Hz (i.e., undamped natural frequency ω_n of 3.1011 rad/s and damping ratio of 2.1985 dB)
- For the case of the minimum allowed bandwidth of 0.7 Hz (see Table 11 of [1]), the dTE results are each multiplied by a factor of $(1.0/0.7)^2$ = 2.04
  - This is due to the factor of ω_n^2 in the denominator of the final equation on the previous slide
  - This means that for a bandwidth of 0.7 Hz, the maximum absolute value of 104 ns computed on the previous slide becomes (104 ns)(2.04) = 212 ns
  - Then, since the steady-state error due to the filter is negative, and assuming max|dTE| without the filter is the 15 ns of row 1 of Table 14 of [1], the lower end of the range of dTE for Table 14 with filtering is -212 ns – 15 ns = -227 ns =(approximately) -230 ns

Conclusions - 1

- All the requirements of IEC/IEEE 60802 [1], Tables 13 and 14 are met, except for the following:
  - For a PTP end instance where all the clocks are stable, the maximum of filtered dTE taken over time and over 300 replications slightly exceeds the ±15 ns limit
  - Examination of the simulation results (numerical output) indicates that this exceedance of 15 ns occurred at exactly one data point on exactly 2 of the 300 replications
    - Maximum dTE of 15.127 ns on replication 239 at 2791 s
    - Maximum dTE of 15.327 ns on replication 244 at 2436 s (omitting exceedances before 2 s due to an initial transient)
  - Note that this requirement was not exceeded for the previous simulation results in [11]
    - The range of dTE is approximately the same here and in [11], but the changes to the model (most likely the assumption that the random distributions for Sync and Pdelay intervals and for residence and pdelay turnaround times are relative to the ideal simulator clock rather than the local clock) have shifted the ranges of results downward
  - If it is felt that more margin is needed, the ±15 ns limit of Table 14 could be slightly increased

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].

Subsequent Simulations

- Work on new system-level simulations (i.e., an HRM with 100 hops) is in progress to verify that the 500 ns max|dTE| objective can be met, using all the revised assumptions since the previous simulations of [4]
- As noted on slide 4, contrary to the desired assumptions DTSE was actually zero for receipt of Pdelay_Req and sending of Pdelay_Resp between nodes 2 and 3; this was due to an error in the input for each simulation case
  - If desired, the simulations could be re-run with this corrected; however, as indicated on slide 4 and in the Appendix, this results in approximately an additional 0.134 ns of DTSE after mean link delay averaging, and should not affect the results appreciably

Thank you

References - 1

[1] IEC/IEEE 60802 Time-Sensitive Networking Profile for Industrial Automation, Draft 2.3, 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

References - 3

[11] Geoffrey M. Garner, *Further 60802 Error Generation Time Series Simulation Results, Version 2*, March 11, 2024 (available at https://www.ieee802.org/1/files/public/docs2024/60802-garner-further-error-generation-time-series-simulation-results-0324-v02.pdf)

[12] David McCall, Figures supplied on March 25, 2024

[13] David McCall, *60802 Time Sync – Mean Link Delay and Timestamp Granularity*, Version 2, March 2024 (available at https://www.ieee802.org/1/files/public/docs2024/60802-McCall-Mean-Link-Delay-Timestamp-Granularity-0324-v02.pdf)

[14] Arthur E. Bryson, Jr. and Yu-Chi Ho, *Applied Optimal Control*, Hemisphere Publishing, 1975.

Appendix – Effect of dTE Prior to applying truncation due to DTSE - 1

- It was indicated on slide 4 that DTSE was set to zero for receipt of Pdelay_Req and sending of Pdelay_Resp between nodes 2 and 3, rather than being chosen randomly from a uniform distribution over [-6 ns, +6 ns]
- In this Appendix, we compute the error in filtered mean link delay that would have been present had this DTSE been included
- After the 1000-sample initialization period, the averaging filter for mean link delay is given by (see slide 17)

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

- where $a_1 = 0.999$, and $b_0 = 0.001$
- The equation for the time evolution of the variance of y_k is given by (see 11.2, Eq. (11.2.9), of [14])

$$P_k = a_1^2 P_{k-1} + b_0^2 Q_k$$

where P_k is the variance of y_k and Q_k is the variance of x_k

Appendix - 2

- In steady state, $P_k = P_{k-1} = P$. Inserting this into the above iteration and solving for P gives

$$P = \frac{b_0^2 Q}{1 - a_1^2}$$

- In addition, the Q_k are the same at each sample k, and equal to the variance of the DTSE. For a uniform distribution over the range [-d, +d], and zero mean, the variance is $Q_k = d^2/3$. Inserting this into the above equation produces

$$P = \frac{b_0^2 d^2}{3(1 - a_1^2)}$$

- Inserting the above values for d, b_0 and a_1 gives $P = 5.0025 \times 10^{-3} d^2 = 0.018\ \mathrm{ns}^2$
- The standard deviation of the successive y_k, i.e., filtered mean link delay values, is the square root of this, i.e., $0.134\ \mathrm{ns}$