Initial Simulation Results for 802.1AS Synchronization Transport with Longer Sync and Pdelay Intervals

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Outline

- Introduction
- HRM
- Model Summary
- Simulation cases and input
- Results
- Conclusions
- Future work

Introduction – 1

- During the initial development of IEEE P802.1AS, there were discussions that considered a Sync interval of 0.01 s and a Pdelay message interval of 0.1 s
  - Jitter/wander accumulation simulations performed at the time (see [3] and [4]) indicated that the end-to-end performance requirements for A/V applications could be met in a network of 7 hops from grandmaster to any slave time-aware system (with suitable endpoint filter bandwidth)
- After it was decided to include 802.11 links in the initial version of 802.1AS, it was desired to increase the Sync interval to 0.1 s, or larger if possible, and the Pdelay message interval to 1 s, or larger if possible
- New simulations are needed to determine if the jitter/wander requirements can be with the longer inter-message intervals

Introduction – 2

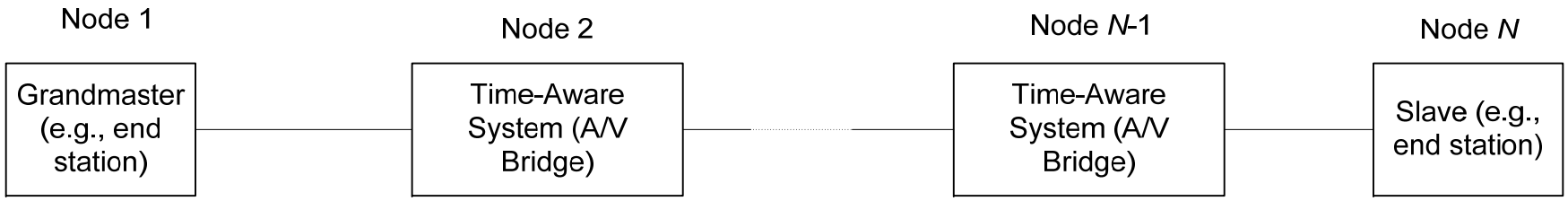
- In addition, since the original simulations were performed, the method of measuring rate offset between a slave time-aware system and the grandmaster was changed
  - Previously, the rate ratio of the grandmaster relative to the slave was measured directly using successive Sync messages
  - With the change, nearest neighbor rate ratio is measured using successive Pdelay_Resp messages
  - Nearest neighbor rate ratio relative to the grandmaster is accumulated in a TLV contained in the Follow_Up message
  - This change needed to be added to the simulator
- In addition, the original simulator used a simplified model that had a fixed time step
  - The model of [1] and [2] was based on the IEEE 1588 Boundary Clock (though it differed in some aspects)
  - The model of [3] and [4] was based on the IEEE 1588 peer-to-peer transparent clock, with syntonization performed using successive Sync message

Introduction – 3

- The modified simulator is discrete-event-based
  - The sending and receiving of Sync, Pdelay_Req, and Pdelay_Resp messages are modeled explicitly
    - For simplicity, the time-aware systems are treated as one-step devices; the performance impact of this is negligible
  - A fixed time step is used between successive discrete events to update filtered variables

Hypothetical Reference Model (HRM)

- Number of hops = *N* – 1 = 7
  - i.e., N = 8 nodes (time aware systems) numbered from 1 to 8, with the grandmaster as node 1



Model Summary – 1

- Model is discrete-event; the events are the sending and receiving of Sync, Pdelay_Req, and Pdelay_Resp messages
- Each node contains a free-running clock, for which the following is specified
  - Frequency tolerance y
    - At initialization, the actual frequency offset is chosen randomly from a uniform distribution over $[-y, y]$
  - Frequency drift D
  - Phase measurement granularity
  - Parameters of power-law noise models:
    - White Phase Modulation (WPM)
    - Flicker Phase Modulation (FPM)
    - White Frequency Modulation (WFM)
    - Flicker Frequency Modulation (FFM)
    - Random Walk Frequency (RWFM)

Model Summary – 2

- For the simulation cases here, only the frequency tolerance and phase measurement granularity are modeled; the drift and noise components are set to zero
  - These will be considered in future simulations, after further consideration of the maximum drift rate assumption for 802.1AS
    - A maximum drift rate of 4 ppm/s is given in the AVB assumptions document [4]; however, a maximum rate of 1 ppm/s has been discussed in the AVB TG. In addition, it has been indicated that both values may be overly conservative.
- **While the clock instability and drift are not considered in the current simulations, it is important that the magnitudes of these effects be considered and their impact be simulated if they are significant**
  - **For example, a linear drift rate of 4 ppm/s, i.e., 4000 ns/s^2, results in a phase change of (0.5)(4000 ns/s^2)(0.125 s)^2 = 31 ns over a 0.125 s sync interval**
  - **This is of the same order of magnitude as the phase measurement granularity**
  - **Depending on the magnitude of the drift, the sync interval, and the assumed model, the effect of clock instability may or may not be significant**

Model Summary – 3

- Each link is associated with a delay model
  - For now, the link delay is fixed, but can be asymmetric
- Times associated with messages; fixed for now
  - Sync interval
  - Pdelay interval
  - Pdelay turnaround time (time between receipt of Pdelay_Req and sending of Pdelay_Resp)
  - Residence time (time between receipt of Sync by a node that is not the Grandmaster (GM), i.e., node $j > 1$ in slide 5, and sending of Sync to node $j+1$)

Model Summary – 4

- The basic operation of the simulator is

```
generateInitialEvents(); /* Sending initial Sync by GM; sending initial
  Pdelay_Req from node j to node j – 1, for j= 2, …, N */
while (timer <= endTime) {
    removeNextEvent();
    computeFreeRunningClockTimesAtTimeOfNextEvent();
    computeUnfilteredSynchronizedTimeEstimateAtTimeOfNextEvent();
    /* based on current estimate of rateRatio relative to GM and most
  recent (freeRunningTime, synchronizedTime) association */
    computeFilteredSynchronizedTimeEstimateAtTimeOfNextEvent();
    eventHandler();
}
```

- The events are maintained in a linked list, in chronological order relative to global timer

Model Summary – 5

- Filter model is the same as that used in [1] – [4]
- In setting the integration time step for the filter, the time between the current and next event is divided into the smallest number of time steps such that the size of the time step is not larger than a specified maximum, i.e.,
  - If T = time between events
  - Δt_{max} = maximum time step (input parameter)
  - Δt = actual time step
  - Then
  - $N_{steps} = \text{ceil}\,(T/\,\Delta t_{max}\,)$
  - $\Delta t = T/N_{steps}$

Model Summary – 6

- The following is a high-level overview of the processing of each event type
- Sending Pdelay_Req event
  - Generate time stamp relative to free-running clock (compute free-running time corresponding to current value of timer)
  - Schedule next sending of Pdelay_Req event and add to linked
- Receipt of Pdelay_Req event
  - Generate time stamp relative to free-running clock (compute free-running time corresponding to current value of timer)
  - Schedule sending of Pdelay_Resp event
- Sending of Pdelay_Resp event
  - Generate time stamp relative to free-running clock (compute free-running time corresponding to current value of timer)
  - Place Pdelay turnaround time in message structure
  - Schedule receipt of Pdelay_Resp event

Model Summary – 6

- Receipt of Pdelay_Resp event
  - Generate time stamp relative to free-running clock (compute free-running time corresponding to current value of timer)
  - Compute neighborRateRatio
    - A granularity for the neighborRateRatio computation can be specified (e.g., based on a given number of bits of precision for the computation)
  - Compute neighborPropDelay
  - Note that there is no new event to generate in this case
- Sending of Sync event
  - Generate time stamp relative to free-running time corresponding to current value of timer)
  - Compute residence time, corrected for cumulativeRateRatio, based on time stamp and saved time stamp (relative to free-running timer) of most recently received Sync
  - Add residence time and current neighborPropDelay to correctionField
  - Schedule receipt of Sync at downstream node

Model Summary – 6

- Receipt of Sync event
  - Generate time stamp relative to free-running time corresponding to current value of timer)
  - Compute correctedMasterTime (GM time estimate), which is the sum of the preciseOriginTimestamp, correctionField, and neighborPropDelay)
  - Compute cumulativeRateRatio relative to GM using received cumulativeRateRatio and current neighborRateRatio
  - Compute unfiltered phase offset, which is the difference between the correctedMasterTime and current local clock time (the time stamp for receipt of the Sync)
    - Note that the (time stamp, correctedMasterTime) becomes the current association of free-running and GM time

Model Parameters Common to All Cases – 1

- Endpoint filter gain peaking = 0.1 dB
- Residence time = 1 ms (fixed)
- Pdelay turnaround time = 1 ms (fixed)
- Link propagation delay = 500 ns (fixed)
  - Links are symmetric
  - PHY latency is assumed symmetric
- Phase (time) measurement granularity = 40 ns
- Frequency measurement granularity = 2.328×10^{-10} (i.e., computations assumed to be done with 32-bit arithmetic)
- No clock noise or clock instability (e.g., constant temperature is assumed)
- Frequencies of free-running oscillators in nodes are chosen randomly at initialization within their tolerance range (a uniform distribution is assumed)

Simulation Cases

Case	sync interval (s)	Pdelay interval (s)	Endpoint filter bandwidth (Hz)	Free-running oscillator frequency tolerance (ppm)	Maximum time Step (s)	Simulation time (s)
1	0.01	0.1	0.01	± 100	0.001	10010
	0.125	1.0				
	0.250	2.0				
2	0.01	0.1	0.01	± 5	0.001	10010
	0.125	1.0				
	0.250	2.0				
3	0.01	0.1	0.001	± 100	0.001	10010
	0.125	1.0				
	0.250	2.0				

Nomenclature for Referring to Case and Subcase

- Each case and subcase is referred to by the following nomenclature:
  - Case x-y or x-y

  where

  x = case number (i.e., 1, 2, or 3)

  y = a 2 or 3 digit integer, where 0.y is the sync interval for the subcase (i.e., ‘01’, ‘125’, or ‘250’)

  This notation is unambiguous for the cases/subcases here, because the same Pdelay interval is used with a given sync interval for the subcases here

  This is not proposed as a general notation; it was simply convenient for this particular presentation

Simulation Subcases

- Subcase ‘01’ represents the sync interval and Pdelay interval (0.01 s and 0.1 s, respectively) previously found to give acceptable performance (with suitable endpoint filter bandwidth)
- Subcase ‘125’ represents the desired sync interval and Pdelay interval (0.125 s and 1.0 s)
- Subcase ‘250’ represents a still longer sync interval and Pdelay interval (0.250 s and 2.0 s)
- Note that the longer sync and Pdelay intervals are chosen to be powers of 2 as required in both 802.1AS and IEEE 1588™-2008

Actual Frequency Offsets for Nodes 1 – 8

- The next slide gives the actual frequency offsets used in the simulation cases
  - They were chosen randomly at initialization from a uniform distribution over the tolerance range
  - Therefore, the values depended on the initial state (seed) of the random number generator
  - The same seed was used for all cases/subcases

Actual Frequency Offsets for Nodes 1 – 8

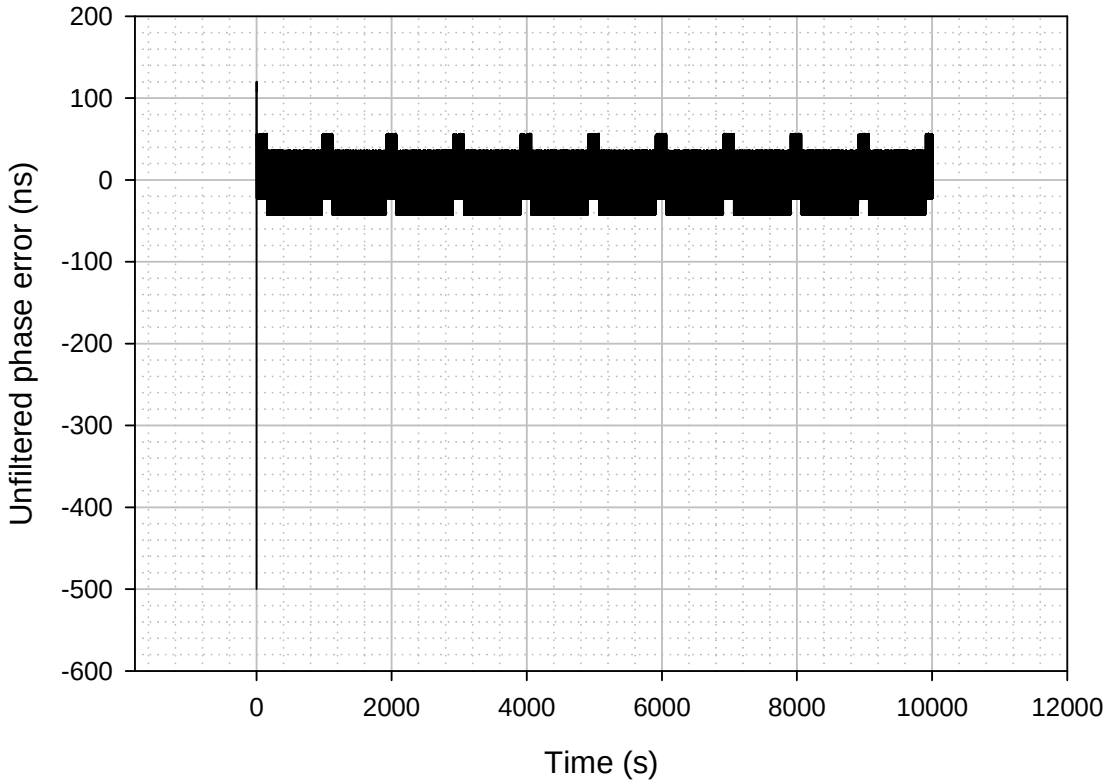
Node	Cases 1 and 3 offset (ppm)	Case 2 offset (ppm)
1	0 (GM)	0 (GM)
2	6.4276	0.32138
3	-55.714	-2.7857
4	32.295	1.6147
5	-53.950	-2.6975
6	38.774	1.9387
7	64.124	3.2062
8	-83.231	-4.1616

General Notes on Reported Simulation Results

- GM is node 1; final node is node 8
- Phase error (filtered and unfiltered) at GM is 0 (and therefore phase error results are not given for node 1)
- Residence time is not needed (and therefore not computed or shown as a result) at nodes 1 and 8 (GM and final node, respectively)
- Correction field value is not needed (and therefore not computed or shown as a result) at node 1 (GM); its value there is zero
- Propagation time between nodes *j* and *j*+1 is relevant for j = 1, 2, …, 7

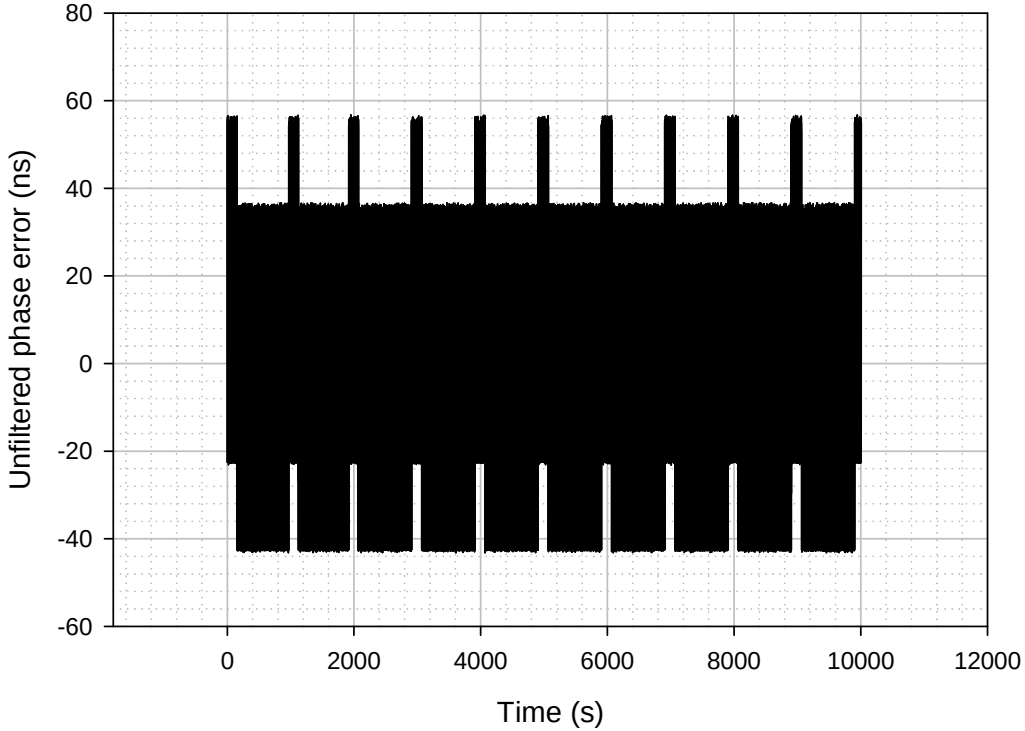
Case 1-01, Node 2 – Unfiltered Phase Error

Case 1-01,Node 2
Unfiltered phase error
Sync Interval = 0.01 s
Pdelay Interval = 0.1 s
Endpoint filter BW = 0.01 Hz
Local oscillator tolerance = +/- 100 ppm
(frequency offsets initialized randomly within tolerance range)



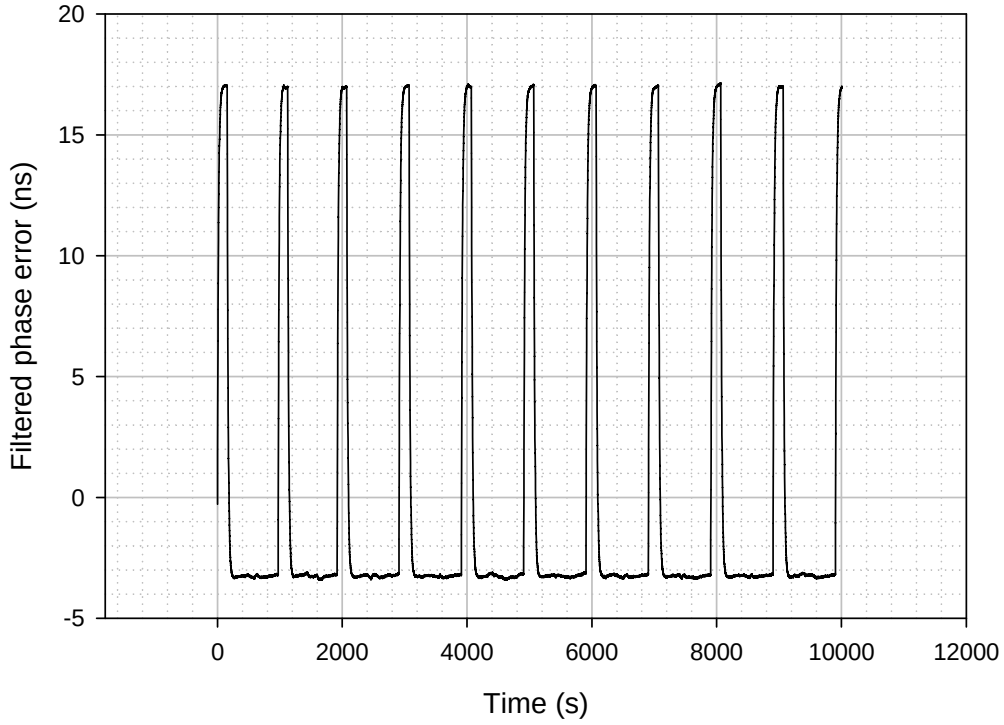
Case 1-01, Node 2 – Unfiltered Phase Error, after initial transient

Case 1-01,Node 2
Unfiltered phase error, initial transient removed
Sync Interval = 0.01 s
Pdelay Interval = 0.1 s
Endpoint filter BW = 0.01 Hz
Local oscillator tolerance = +/- 100 ppm
(frequency offsets initialized randomly within tolerance range)



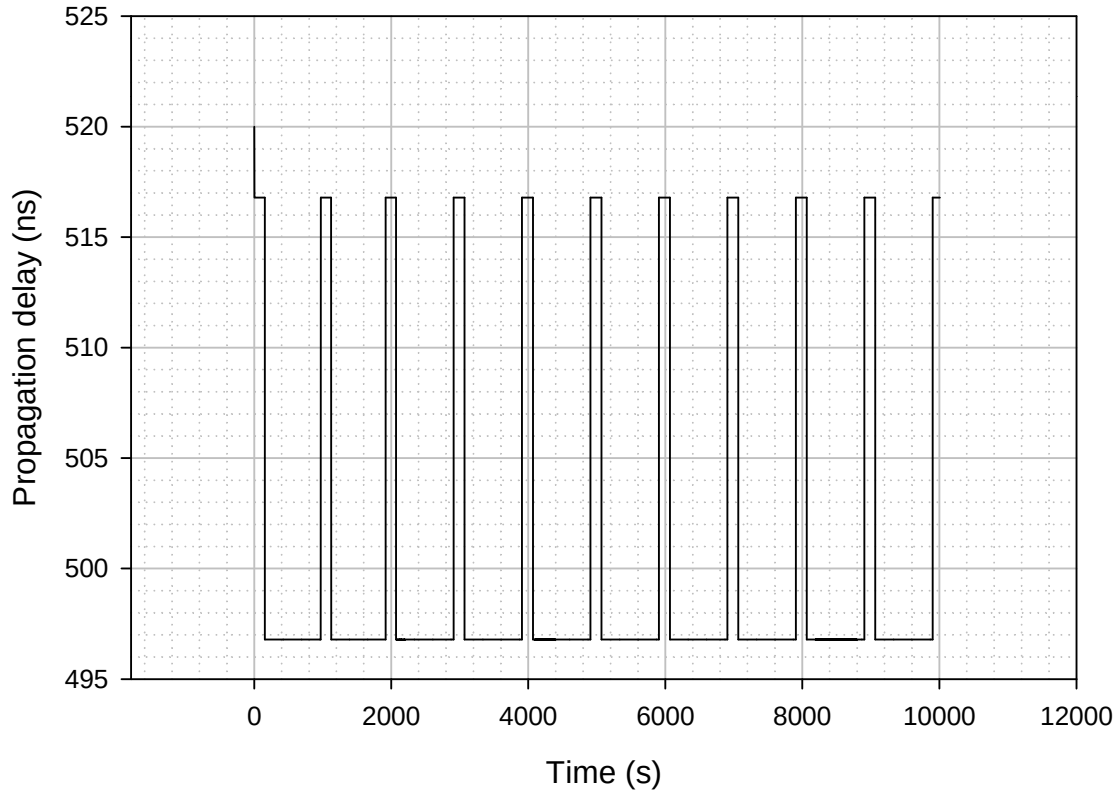
Case 1-01, Node 2 – Filtered Phase Error

Case 1-01,Node 2
Filtered phase error
Sync Interval = 0.01 s
Pdelay Interval = 0.1 s
Endpoint filter BW = 0.01 Hz
Local oscillator tolerance = +/- 100 ppm
(frequency offsets initialized randomly within tolerance range)



Case 1-01, Node 1 to 2 Propagation Delay

Case 1-01,Node 1 to 2 propagation delay
(after initialization)
Sync Interval = 0.01 s
Pdelay Interval = 0.1 s
Endpoint filter BW = 0.01 Hz
Local oscillator tolerance = +/- 100 ppm
(frequency offsets initialized randomly within tolerance range)



Case 1-01, Node 2 Results – 1

- The unfiltered phase error at node 2 shows periodic jumps, on the order of 20 ns, approximately every 1000 s
- This is apparently due to periodic jumps, with 1000 s period, in the node 1 to node 2 propagation delay that are on the order of 20 ns
- The jumps are due to truncation of the time stamp values to the next lower multiple of 40 ns, i.e., of the phase measurement granularity
- Recall

$$\text{neighborPropDelay} = \frac{(T_4 - T_1) - (T_3 - T_2)}{2}$$

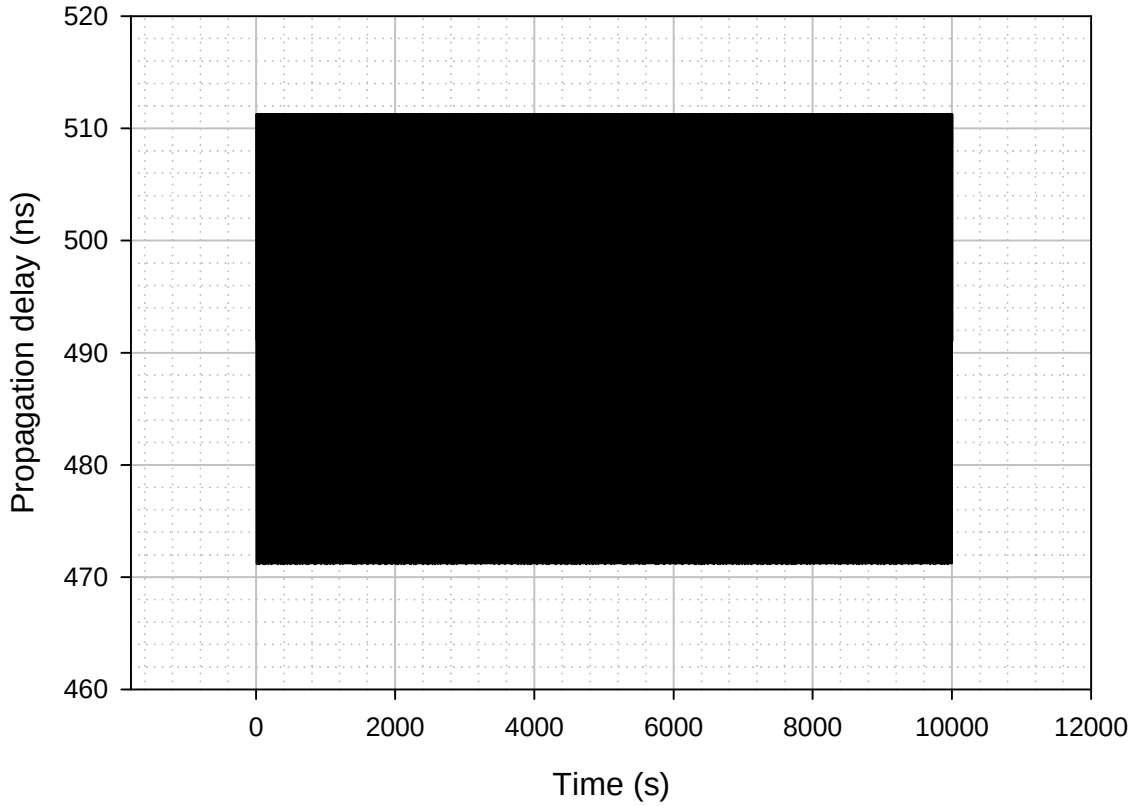
- The time stamps T_1 and T_4 are taken at node 2
  - When T_4 just crosses a multiple of 40 ns, the decrease in T_4 due to truncation goes from 40 ns to 0, and neighborPropDelay increases by 20 ns
  - When T_1 just crosses a multiple of 40 ns, the decrease in T_1 due to truncation goes from 40 ns to 0, and neighborPropDelay decreases by 20 ns
  - A jump does not occur if both time stamps cross or don't cross a multiple of 40 ns; it only occurs when one time stamp crosses

Case 1-01, Node 2 Results – 2

- Since the Pdelay turnaround time is 0.001 s and therefore a multiple of 40 ns, there is no corresponding effect due to T_2 and T_3 (but , in general, there would be)
- The resulting phase error due to this effect can be reduced using propagation time averaging
  - This was initially described in [5]
  - A companion presentation [6] (to the current one) gives initial results comparing the jitter/wander performance with and without propagation time averaging
- The steady-state peak-to-peak total unfiltered phase error is approximately 100 ns
- The steady-state peak-to-peak total filtered phase error is approximately 20 ns
  - The 0.01 Hz endpoint filter removes the fast variation, but the slow variation of magnitude 20 ns, due to the propagation time, remains

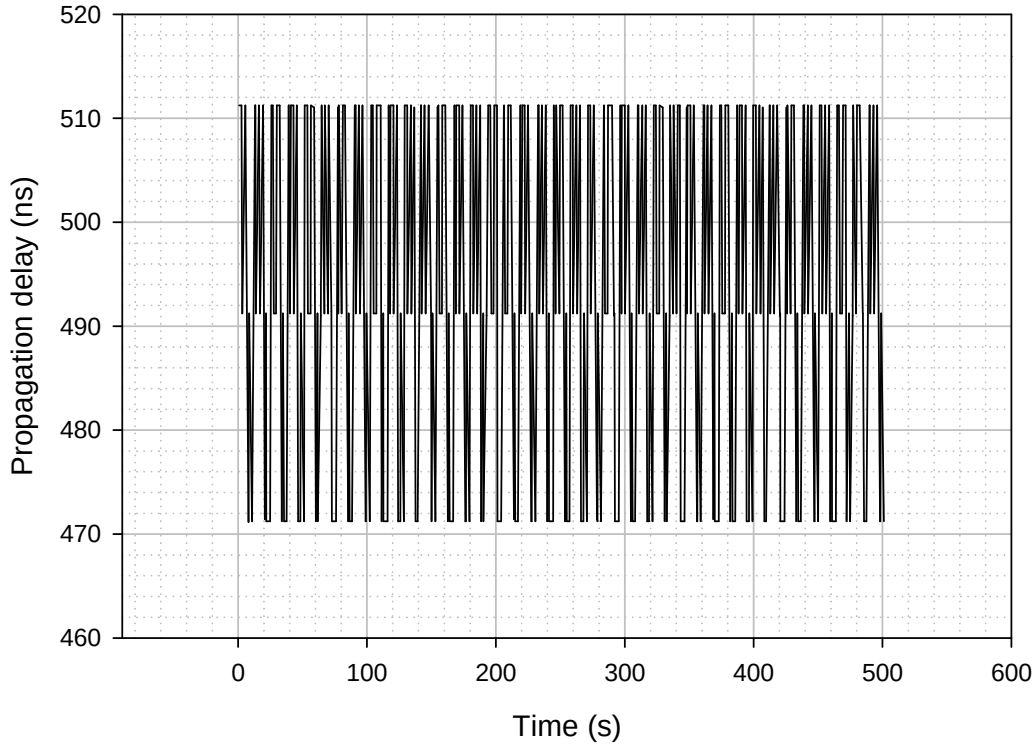
Case 1-01, Node 2 to 3 Propagation Delay

Case 1-01,Node 2 to 3 propagation delay
(after initialization)
Sync Interval = 0.01 s
Pdelay Interval = 0.1 s
Endpoint filter BW = 0.01 Hz
Local oscillator tolerance = +/- 100 ppm
(frequency offsets initialized randomly within tolerance range)



Case 1-01, Node 2 to 3 Propagation Delay, Detail of First 500 s

Case 1-01,Node 2 to 3 propagation delay
(after initialization)
detail of first 500 s
Sync Interval = 0.01 s
Pdelay Interval = 0.1 s
Endpoint filter BW = 0.01 Hz
Local oscillator tolerance = +/- 100 ppm
(frequency offsets initialized randomly within tolerance range)

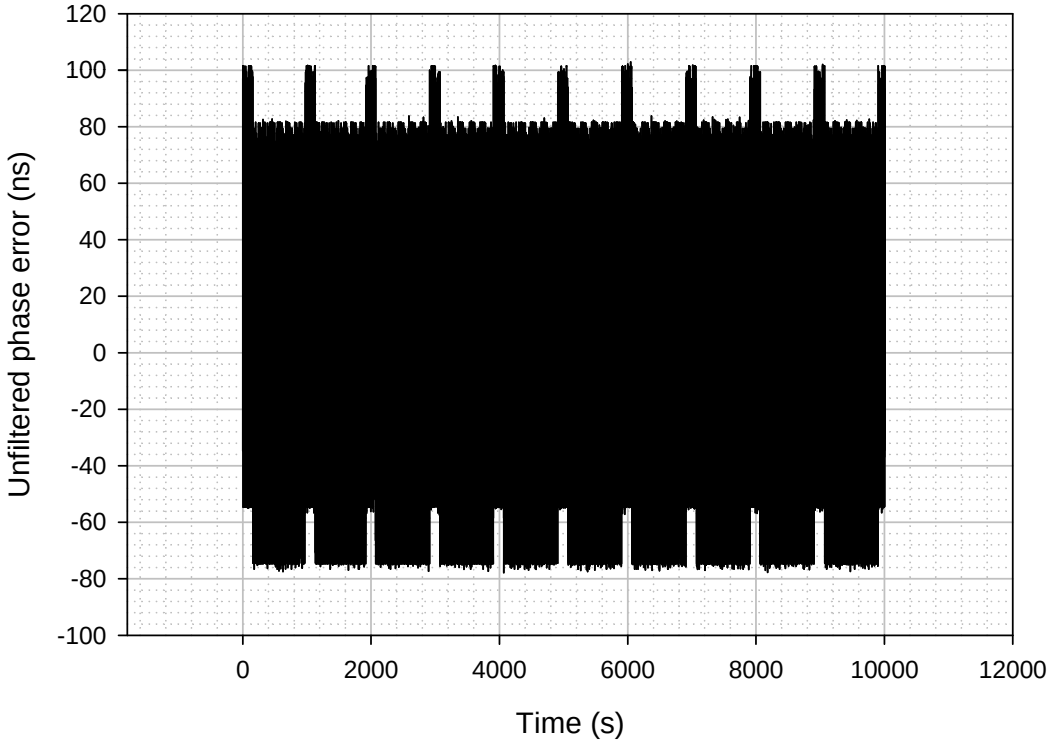


Case 1-01, Node 3 Results – 1

- The node 2 to node 3 propagation time measurement shows a much faster variation than the node 1 to node 2 measurement
  - The period is on the order of 8 – 10 s, i.e., it is much less than the 1000 s obtained for the node 1 to node 2 propagation time measurement
- The period depends on the particular frequency offset between the adjacent nodes, because the jump occurs only when T_4 is truncated and T_1 is not truncated, or vice-versa
- In general, the period is longer for smaller frequency offsets, but there are exceptions to this

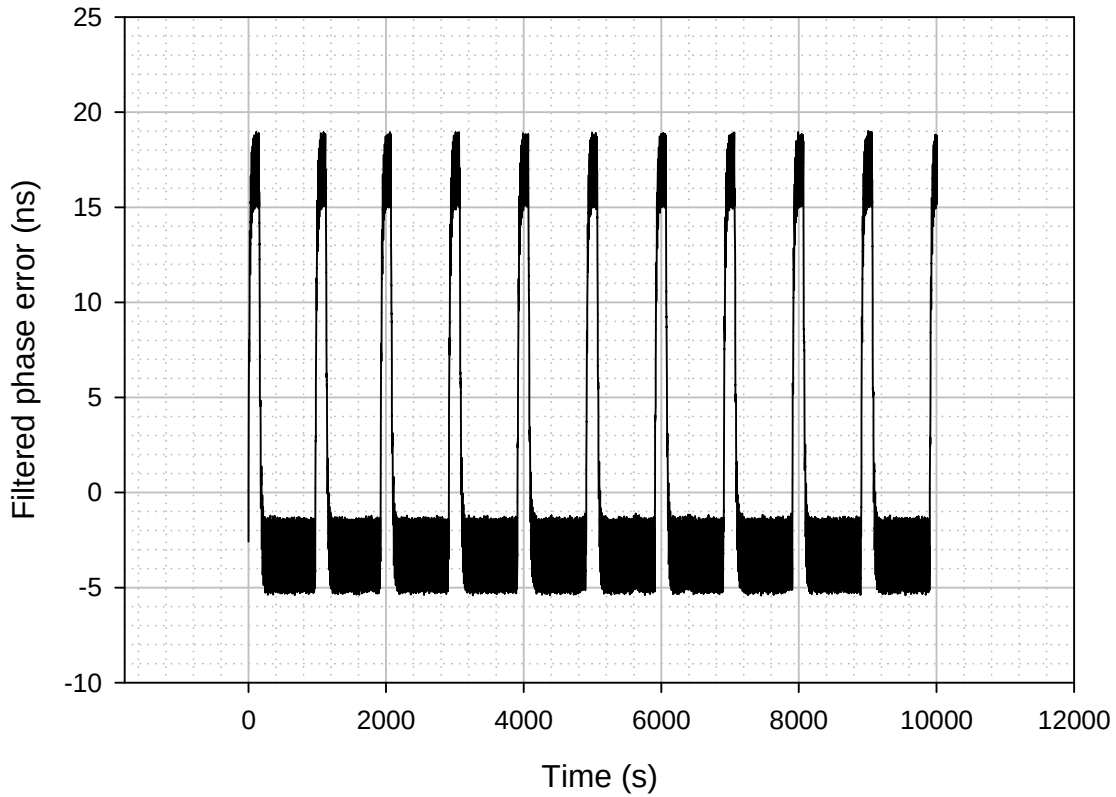
Case 1-01, Node 3 – Unfiltered Phase Error, after initial transient

Case 1-01,Node 3
Unfiltered phase error, initial transient removed
Sync Interval = 0.01 s
Pdelay Interval = 0.1 s
Endpoint filter BW = 0.01 Hz
Local oscillator tolerance = +/- 100 ppm
(frequency offsets initialized randomly within tolerance range)



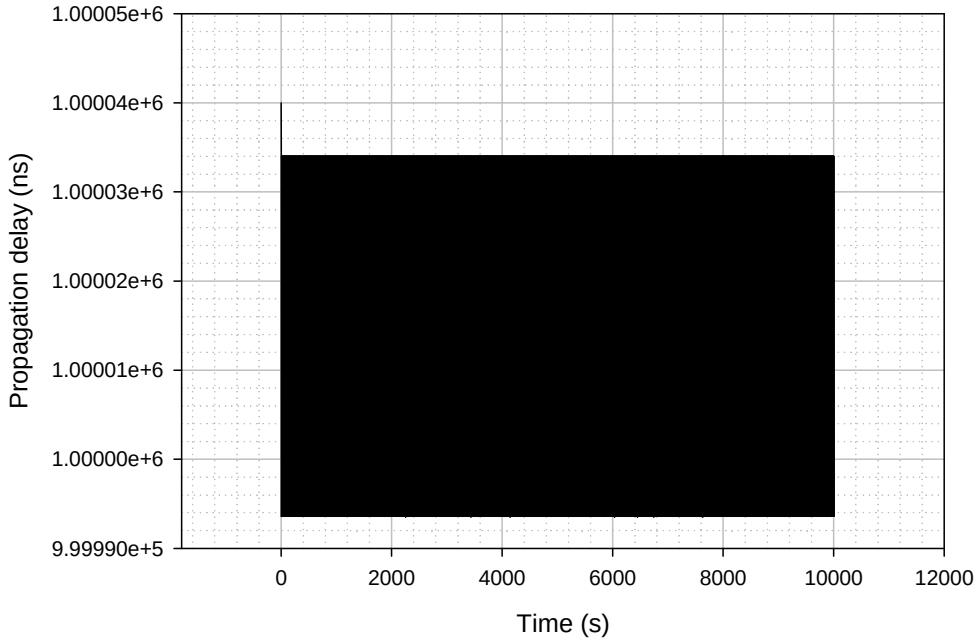
Case 1-01, Node 3 – Filtered Phase Error

Case 1-01,Node 3
Filtered phase error
Sync Interval = 0.01 s
Pdelay Interval = 0.1 s
Endpoint filter BW = 0.01 Hz
Local oscillator tolerance = +/- 100 ppm
(frequency offsets initialized randomly within tolerance range)



Case 1-01, Node 2 – Residence Time

Case 1-01,Node 2 residence time
(after initialization)
Sync Interval = 0.01 s
Pdelay Interval = 0.1 s
Endpoint filter BW = 0.01 Hz
Local oscillator tolerance = +/- 100 ppm
(frequency offsets initialized randomly within tolerance range)



Case 1-01, Node 3 Results – 2

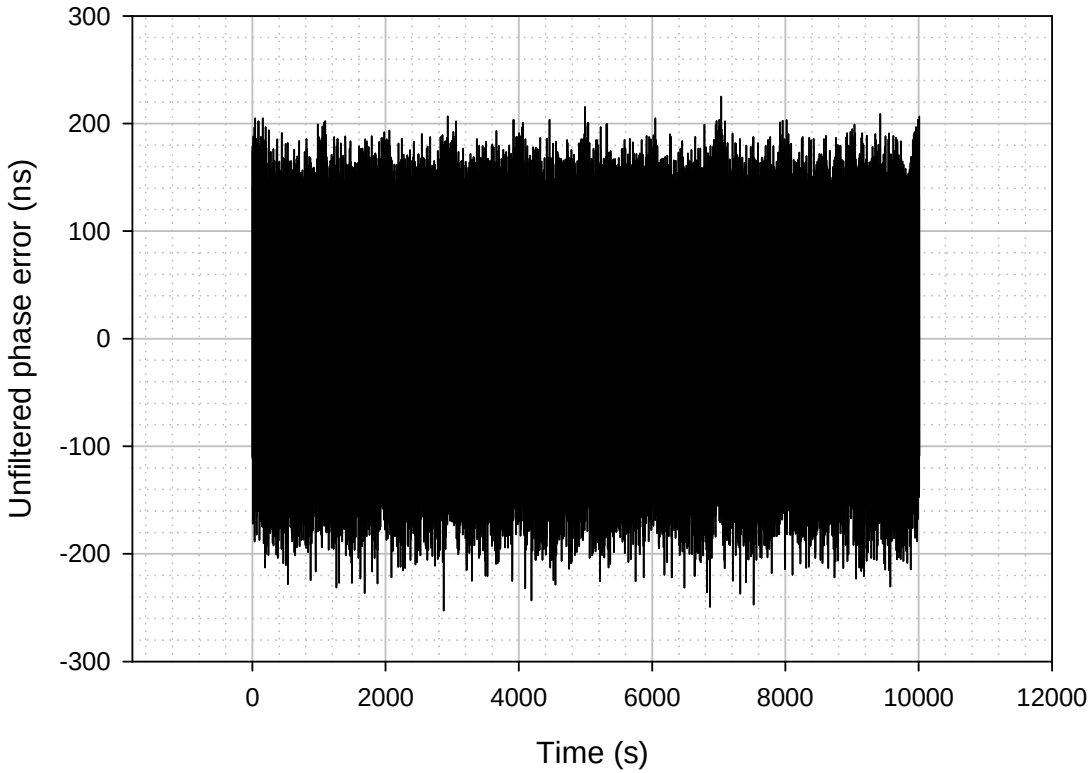
- The unfiltered phase error at node 3 shows the same 20 ns jumps, with period of approximately 1000 s, as shown by node 2
- However, the peak-to-peak unfiltered phase error (in steady-state) is now approximately 180 ns, compared to 100 ns for node 2
- The increase in the peak-to-peak is due to the added variation in node 2 to node 3 propagation time and node 2 residence time
  - 40 ns variation for node 2 to node 3 propagation time
  - 40 ns variation for node 2 residence time
- The periods of these effects are small compared to 1000 s
  - Therefore, the resulting unfiltered phase variation at node 3 has the 20 ns jumps, with period of 1000 s, due to the node 1 to node 2 propagation time measurement, and the much faster variation due to node 2 to node 3 propagation time and node 2 residence time

Case 1-01, Node 3 Results – 2

- The peak-to-peak filtered phase error is approximately 25 ns
  - The filtered phase error shows the same 20 ns jumps as the unfiltered phase error
  - Between jumps, the peak-to-peak variation is approximately 4 ns
  - This is much smaller than 20 ns, though still exceeds some of the application MTIE masks (jitter/wander requirements); this will be discussed shortly

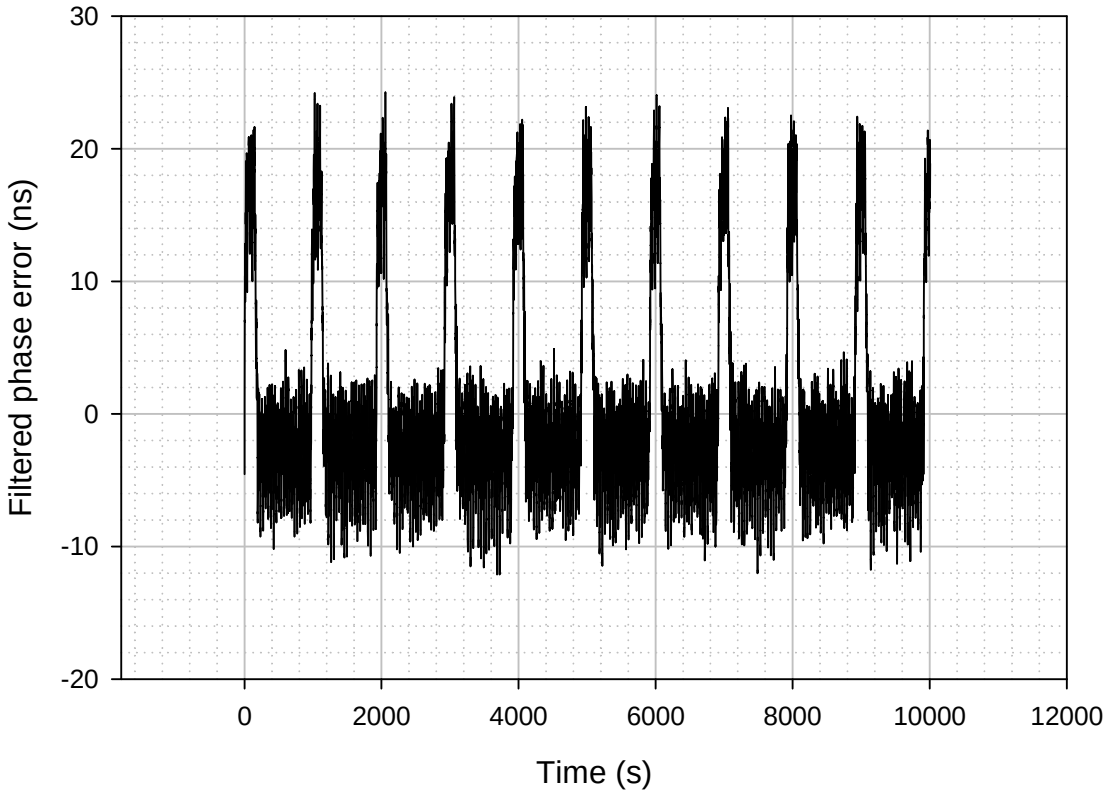
Case 1-01, Node 8 – Unfiltered Phase Error, after initial transient

Case 1-01,Node 8
Unfiltered phase error, initial transient removed
Sync Interval = 0.01 s
Pdelay Interval = 0.1 s
Endpoint filter BW = 0.01 Hz
Local oscillator tolerance = +/- 100 ppm
(frequency offsets initialized randomly within tolerance range)



Case 1-01, Node 8 – Filtered Phase Error

Case 1-01,Node 8
Filtered phase error
Sync Interval = 0.01 s
Pdelay Interval = 0.1 s
Endpoint filter BW = 0.01 Hz
Local oscillator tolerance = +/- 100 ppm
(frequency offsets initialized randomly within tolerance range)

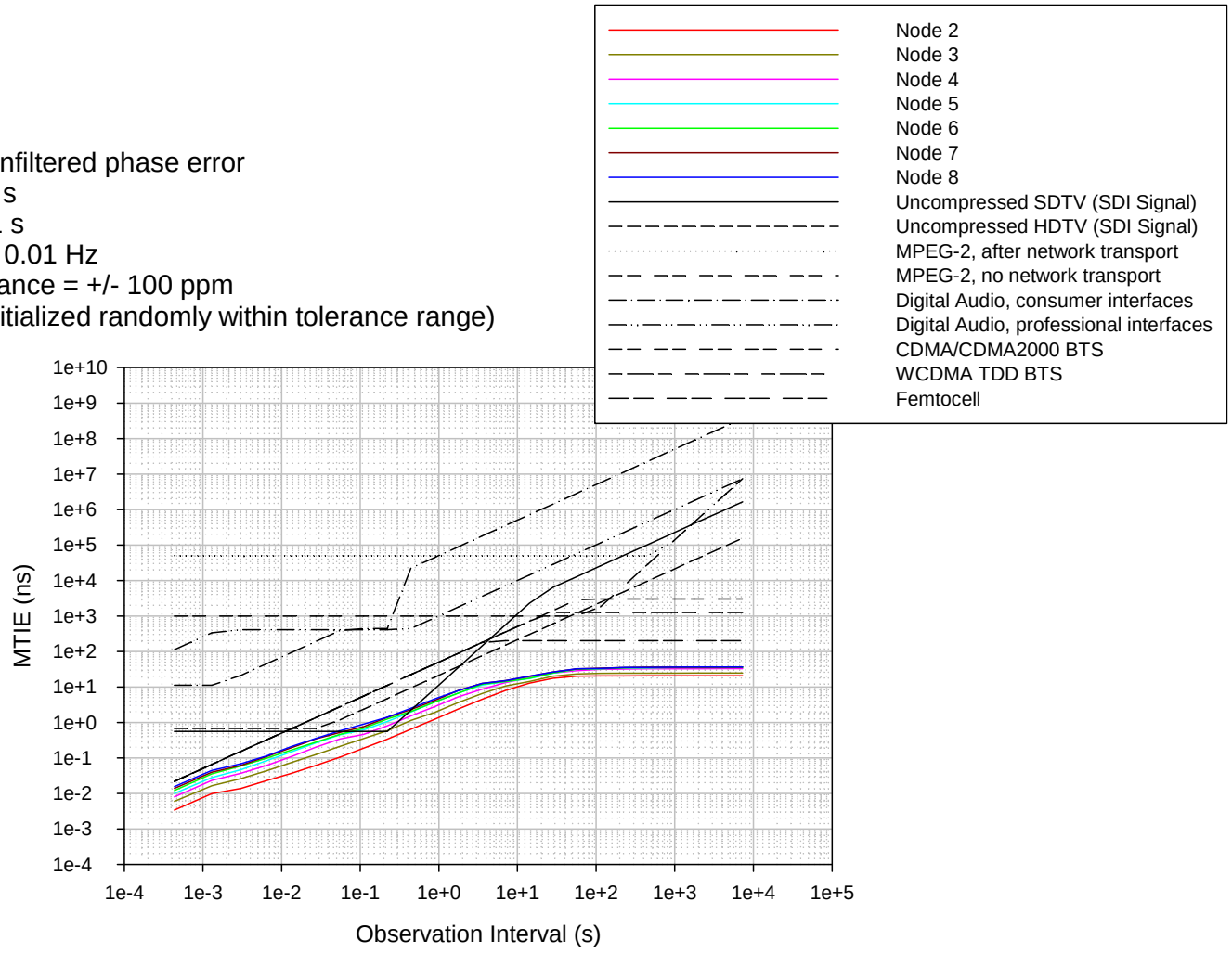


Case 1-01, Node 8 Results

- The peak-to-peak, unfiltered phase error at node 8 is approximately 480 ns
- The 20 ns jumps with 1000 ns period are no longer visible on the scale of the plot
  - The unfiltered phase error at node 8 includes the sum of the propagation times between each successive pair of nodes, plus the residence times at the intermediate nodes (nodes 2 – 7)
  - For this example, only the node 1 to 2 propagation time shows the long period phase jumps
- The peak-to-peak, filtered phase error at node 8 is approximately 36 ns
  - The 20 ns phase jumps are evident here; the larger variation in the unfiltered phase that masked them has been removed by the filtering
  - Between jumps, the unfiltered phase variation is approximately 17 ns

Case 1-01, Filtered Phase Error MTIE

Case 1-01, MTIE - unfiltered phase error
Sync Interval = 0.01 s
Pdelay Interval = 0.1 s
Endpoint filter BW = 0.01 Hz
Local oscillator tolerance = +/- 100 ppm
(frequency offsets initialized randomly within tolerance range)

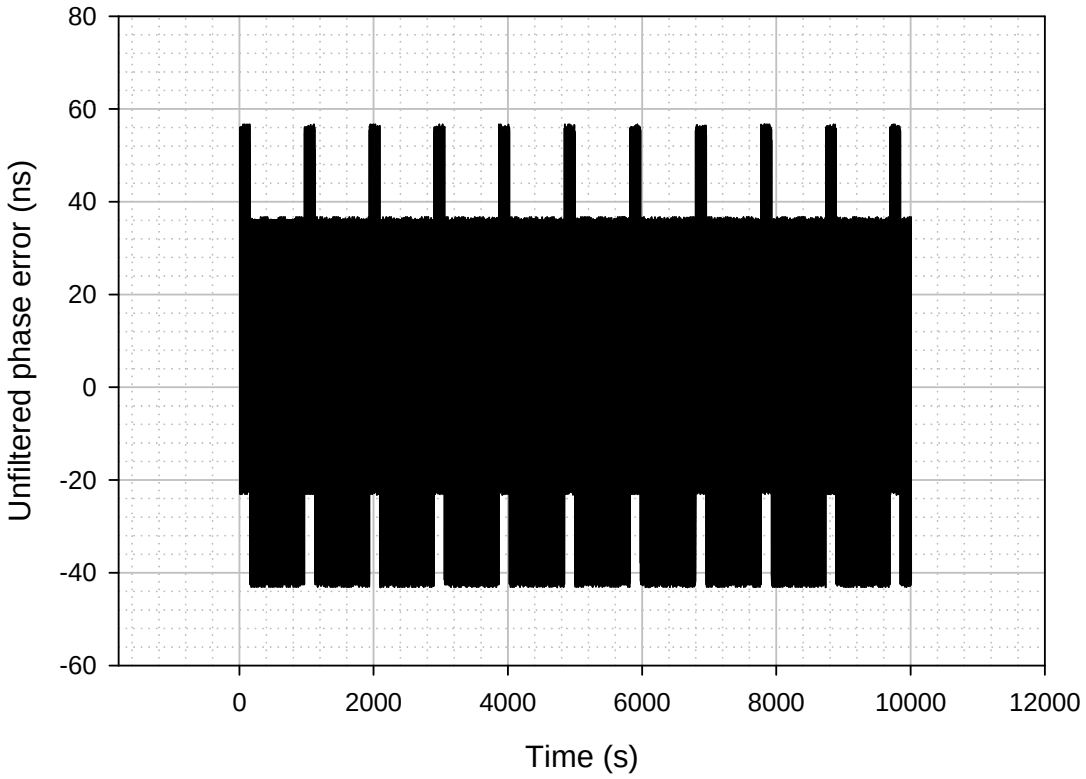


Case 1-01, Node 1 – 8 Jitter and Wander (MTIE) Results

- The previous slide shows MTIE results for the filtered phase at nodes 1 – 8, along with various MTIE masks
  - The MTIE masks are equivalent to jitter and wander requirements for the respective applications
  - The MTIE masks for uncompressed video, MPEG video, and consumer and professional audio are taken from [7] and the references given there
  - The MTIE masks for CDMA, CDMA2000, and WCDMA cellular base stations are equivalent to the requirements given in [8] and [9] (and are derived using the methodology of [7])
  - The MTIE mask for Femtocell base stations is equivalent to the requirements given in [9] (and is derived using the methodology of [7])
- All the requirements are met by the filtered phase at the egress of each node, with the exception of the uncompressed standard definition (SDI video) signal
- The filtered phase meets the uncompressed standard definition video signal requirement at node 2, but exceeds it at nodes 3 – 8 (just barely at node 3)

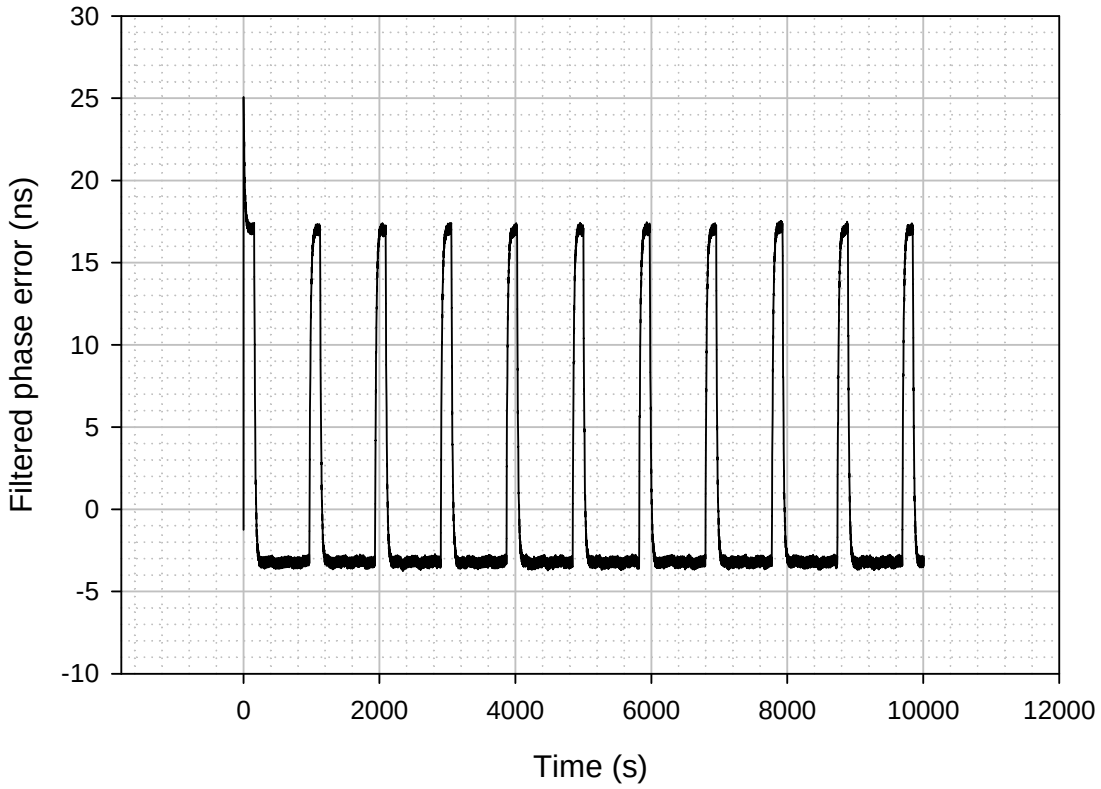
Case 1-125, Node 2 – Unfiltered Phase Error, after initial transient

Case 1-125,Node 2
Unfiltered phase error, initial transient removed
Sync Interval = 0.125 s
Pdelay Interval = 1.0 s
Endpoint filter BW = 0.01 Hz
Local oscillator tolerance = +/- 100 ppm
(frequency offsets initialized randomly within tolerance range)



Case 1-125, Node 2 – Filtered Phase Error

Case 1-125,Node 2
Filtered phase error
Sync Interval = 0.125 s
Pdelay Interval = 1.0 s
Endpoint filter BW = 0.01 Hz
Local oscillator tolerance = +/- 100 ppm
(frequency offsets initialized randomly within tolerance range)

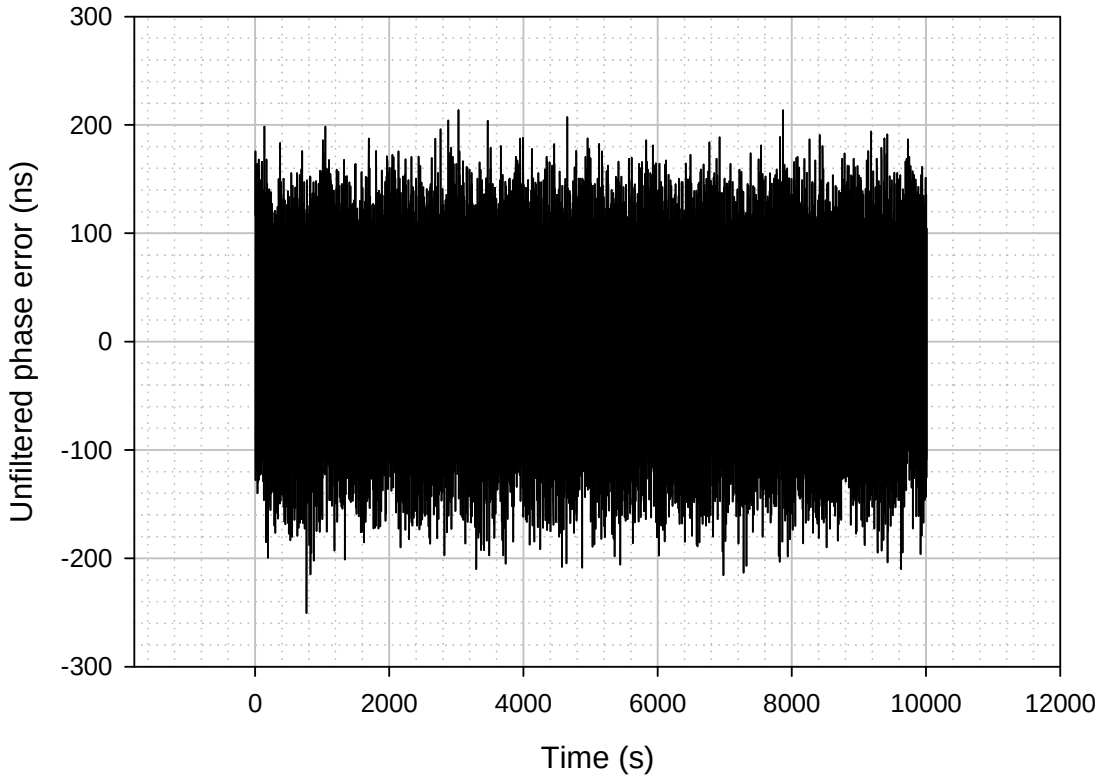


Case 1-125, Node 3 Results

- The unfiltered phase error at node 2 for the 0.125 s sync interval and 1.0 s Pdelay interval case is very similar (appears almost identical) to the 0.01 s sync interval and 0.1 s Pdelay interval case
- The node 1 to node 2 propagation delay here (see backup material at end) shows the same characteristic as in case 1-01
- The filtered error shows the same 20 ns phase jumps with period of approximately 1000 s
- However, there is greater filtered phase variation between jumps, most likely due to the longer sync interval

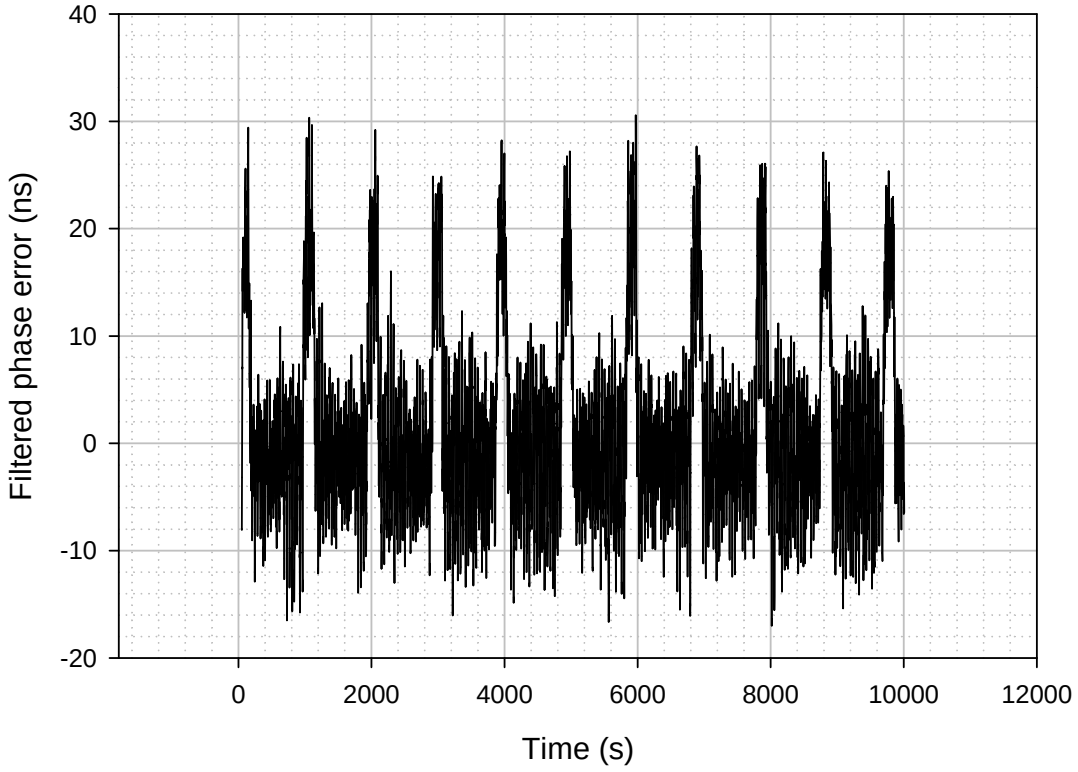
Case 1-125, Node 8 – Unfiltered Phase Error, after initial transient

Case 1-125,Node 8
Unfiltered phase error, initial transient removed
Sync Interval = 0.125 s
Pdelay Interval = 1.0 s
Endpoint filter BW = 0.01 Hz
Local oscillator tolerance = +/- 100 ppm
(frequency offsets initialized randomly within tolerance range)



Case 1-125, Node 8 – Filtered Phase Error

Case 1-125,Node 8
Filtered phase error (initial transient removed)
Sync Interval = 0.125 s
Pdelay Interval = 1.0 s
Endpoint filter BW = 0.01 Hz
Local oscillator tolerance = +/- 100 ppm
(frequency offsets initialized randomly within tolerance range)

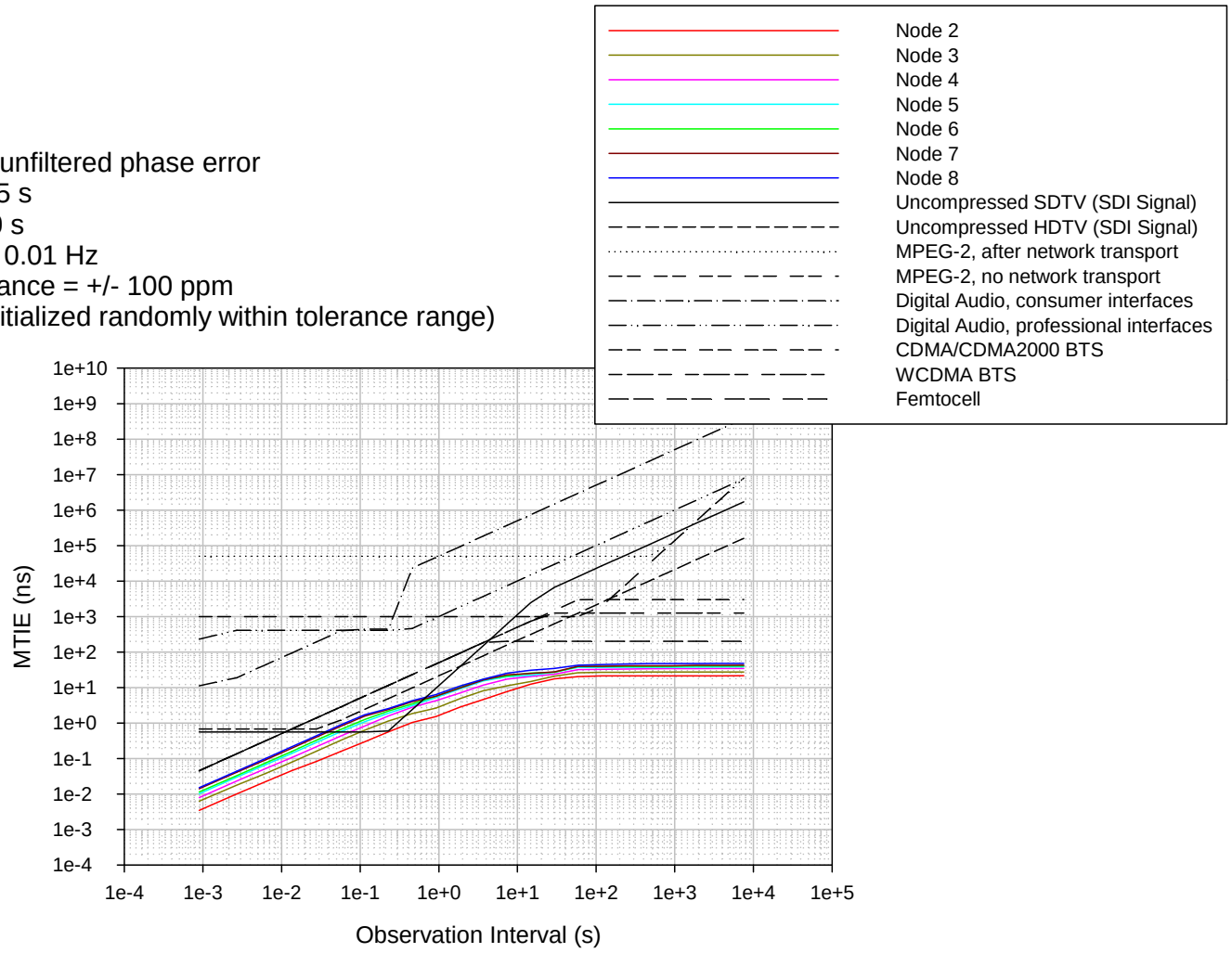


Case 1-125, Node 8 Results

- The unfiltered phase error at node 8 for case 1-125 is approximately 480 ns, i.e., it is approximately the same as for case 1-01
  - The variance of the unfiltered phase error is slightly reduced
- The filtered phase error for case 1-125 is approximately 48 ns, compared to 36 ns for case 1-01
  - The 20 ns phase jumps are evident, and the variation between phase jumps are larger (i.e., it is now around 30 ns, compared to 17 ns for case 1-01)

Case 1-125, Filtered Phase Error MTIE

Case 1-125, MTIE - unfiltered phase error
Sync Interval = 0.125 s
Pdelay Interval = 1.0 s
Endpoint filter BW = 0.01 Hz
Local oscillator tolerance = +/- 100 ppm
(frequency offsets initialized randomly within tolerance range)

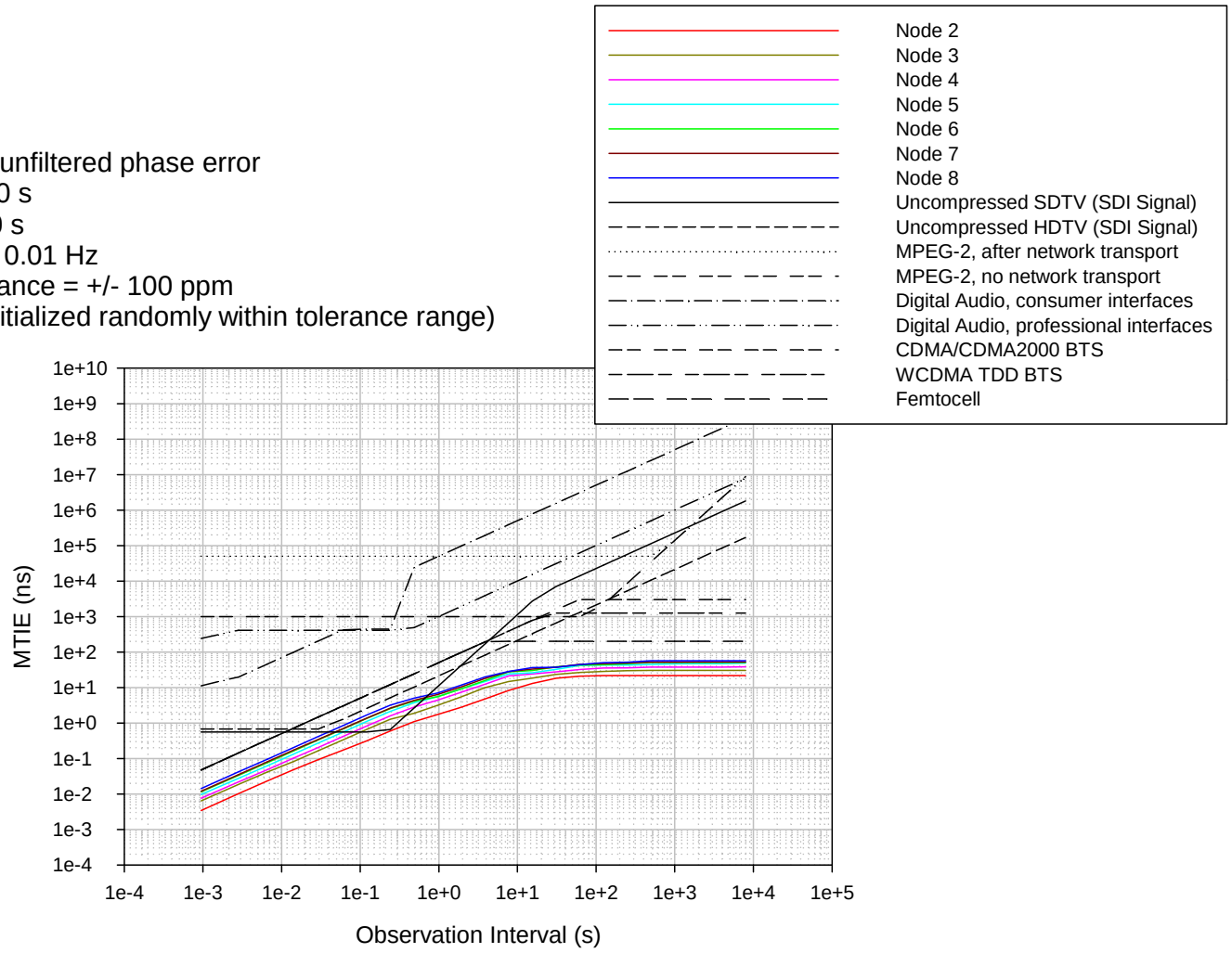


Case 1-125, Node 1 – 8 Jitter and Wander (MTIE) Results

- MTIE has increased for observation intervals longer than approximately 0.01 s
- All the requirements other than for the standard definition SDI video signal are still met, though the results are somewhat closer to the high-definition SDI video mask
  - The filtered phase MTIE now exceeds the standard definition mask at the egress of all the nodes (for case 1-01, it was within the mask at node 2)
- **Overall, the results are not appreciably different when the sync interval is increased to 0.125 s and the Pdelay interval to 1.0 s**
  - The meeting or not meeting of the requirements is the same in both subcases

Case 1-250, Filtered Phase Error MTIE

Case 1-250, MTIE - unfiltered phase error
Sync Interval = 0.250 s
Pdelay Interval = 2.0 s
Endpoint filter BW = 0.01 Hz
Local oscillator tolerance = +/- 100 ppm
(frequency offsets initialized randomly within tolerance range)

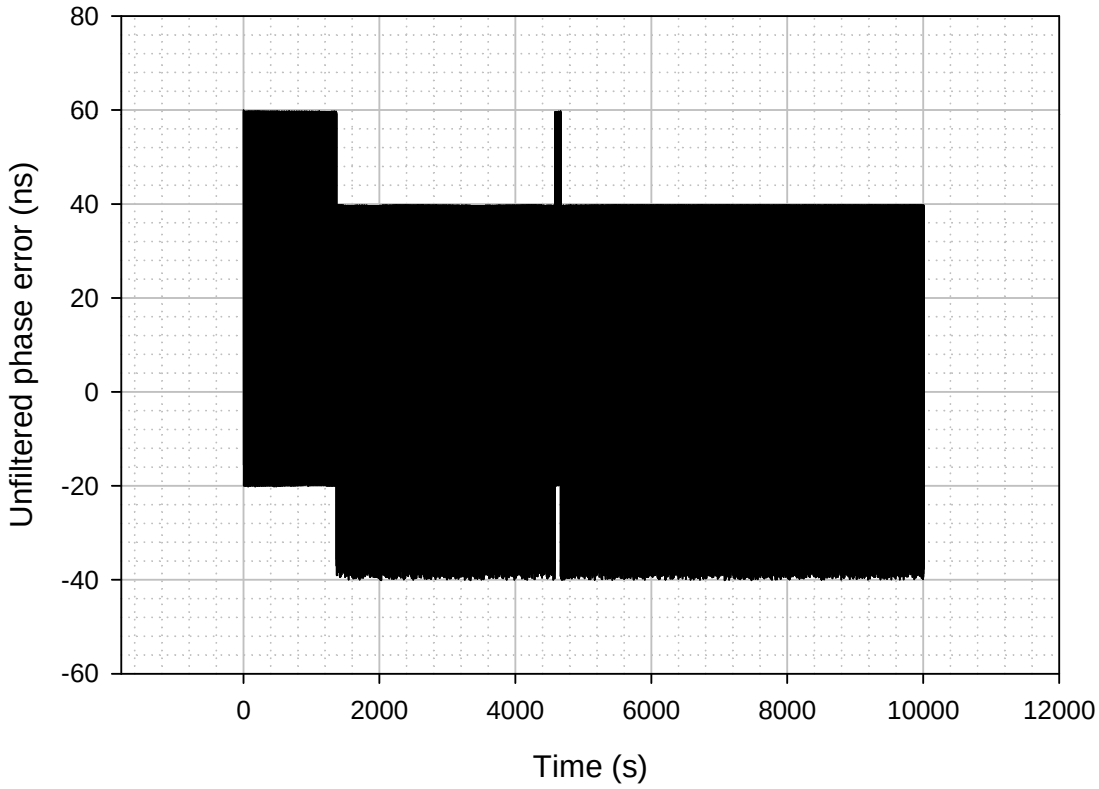


Case 1-250, Node 1 – 8 Jitter and Wander (MTIE) Results

- Detailed results for case 1-250 (0.250 s sync interval, 2.0 s Pdelay interval) are contained in backup material
- MTIE results are very similar to case 1-125
- **Overall, the results are not appreciably different when the sync interval is increased to 0.250 s and the Pdelay interval to 2.0 s, compared to cases 1-01 and 1-125**
  - The meeting or not meeting of the requirements is the same in all subcases

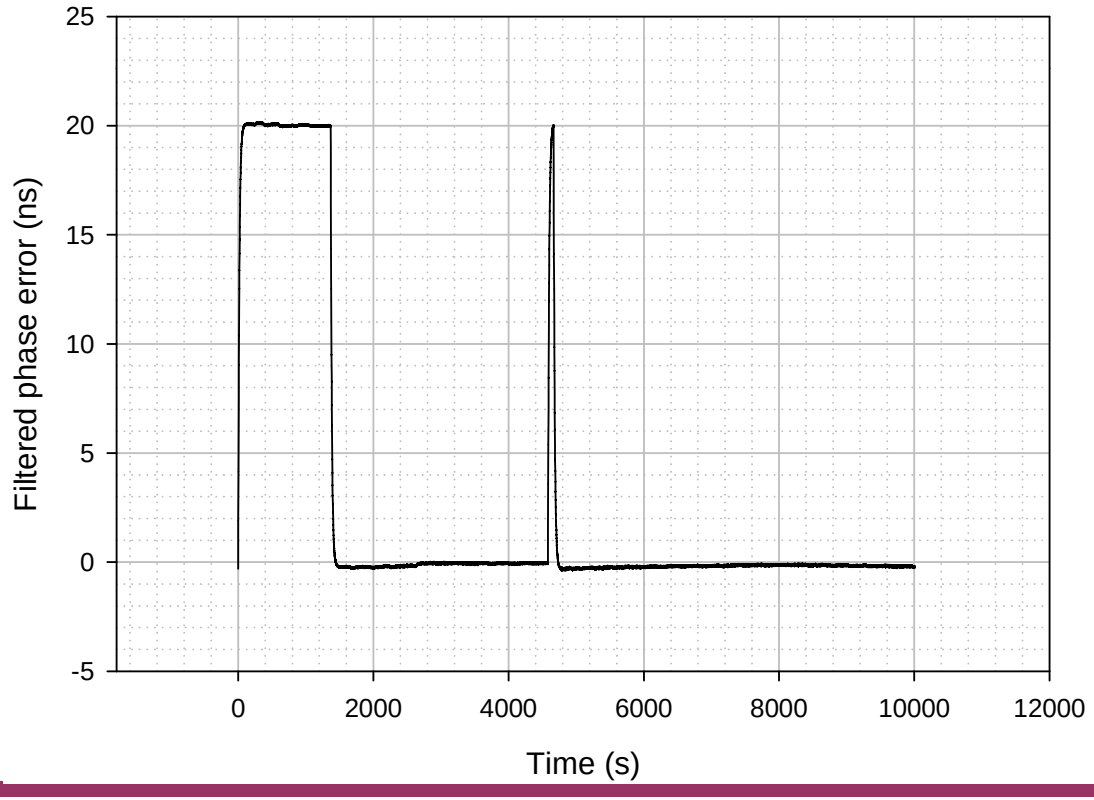
Case 2-01, Node 2 – Unfiltered Phase Error after initial transient

Case 2-01,Node 2
Unfiltered phase error, initial transient removed
Sync Interval = 0.01 s
Pdelay Interval = 0.1 s
Endpoint filter BW = 0.01 Hz
Local oscillator tolerance = +/- 5 ppm
(frequency offsets initialized randomly within tolerance range)



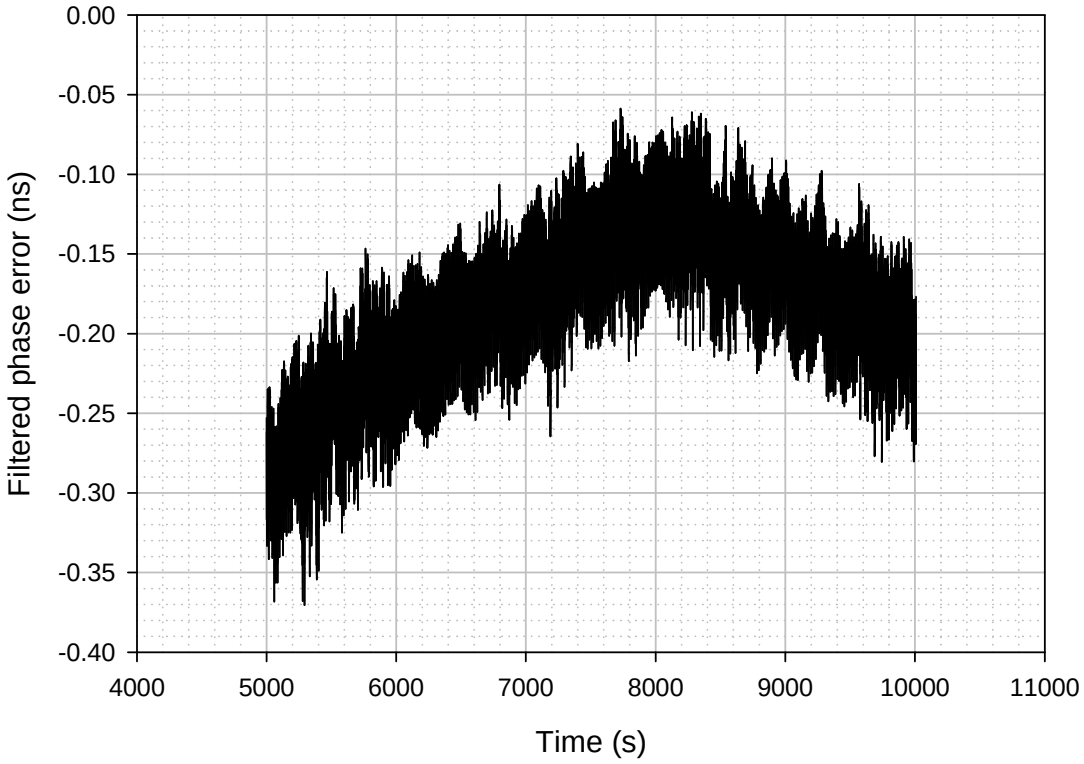
Case 2-01, Node 2 – Filtered Phase Error

Case 2-01,Node 2
Filtered phase error
Sync Interval = 0.01 s
Pdelay Interval = 0.1 s
Endpoint filter BW = 0.01 Hz
Local oscillator tolerance = +/- 5 ppm
(frequency offsets initialized randomly within tolerance range)



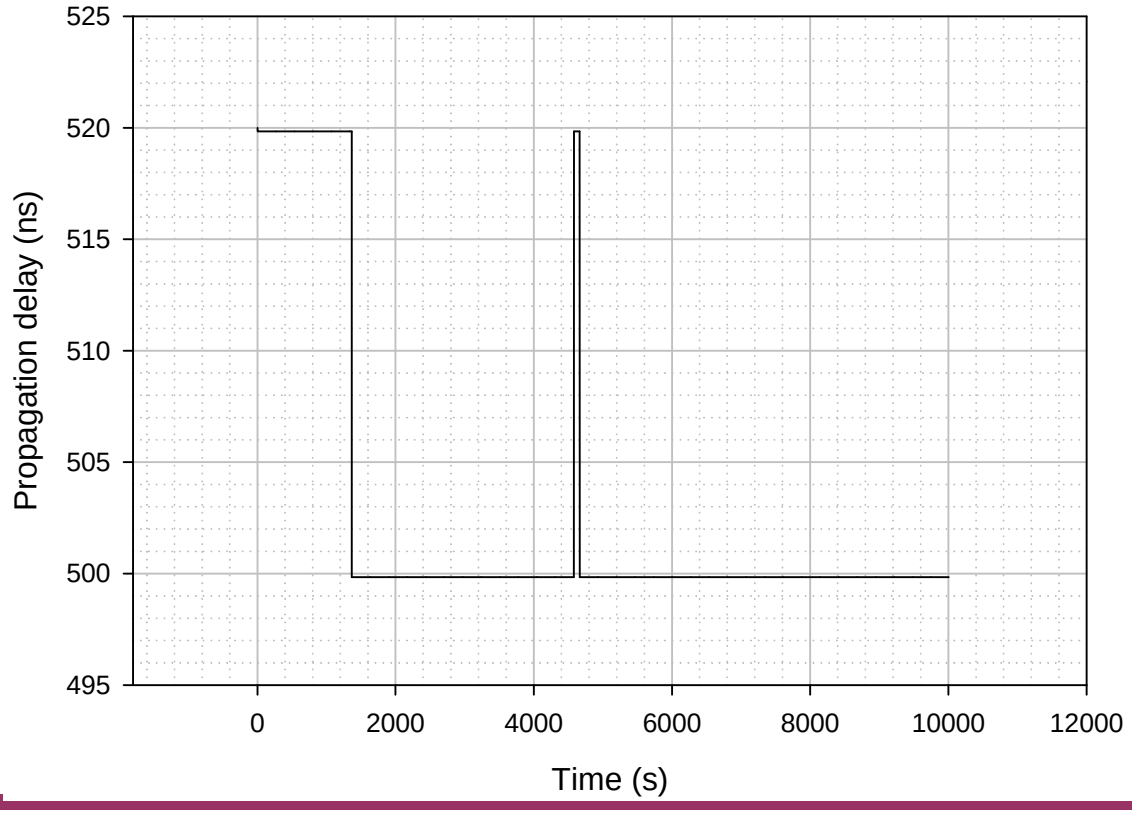
Case 2-01, Node 2 – Filtered Phase Error, Detail after 5000 s

Case 2-01,Node 2
Filtered phase error, detail after 5000 s
Sync Interval = 0.01 s
Pdelay Interval = 0.1 s
Endpoint filter BW = 0.01 Hz
Local oscillator tolerance = +/- 5 ppm
(frequency offsets initialized randomly within tolerance range)



Case 2-01, Node 1 to 2 Propagation Delay

Case 2-01,Node 1 to 2 propagation delay
(after initialization)
Sync Interval = 0.01 s
Pdelay Interval = 0.1 s
Endpoint filter BW = 0.01 Hz
Local oscillator tolerance = +/- 5 ppm
(frequency offsets initialized randomly within tolerance range)

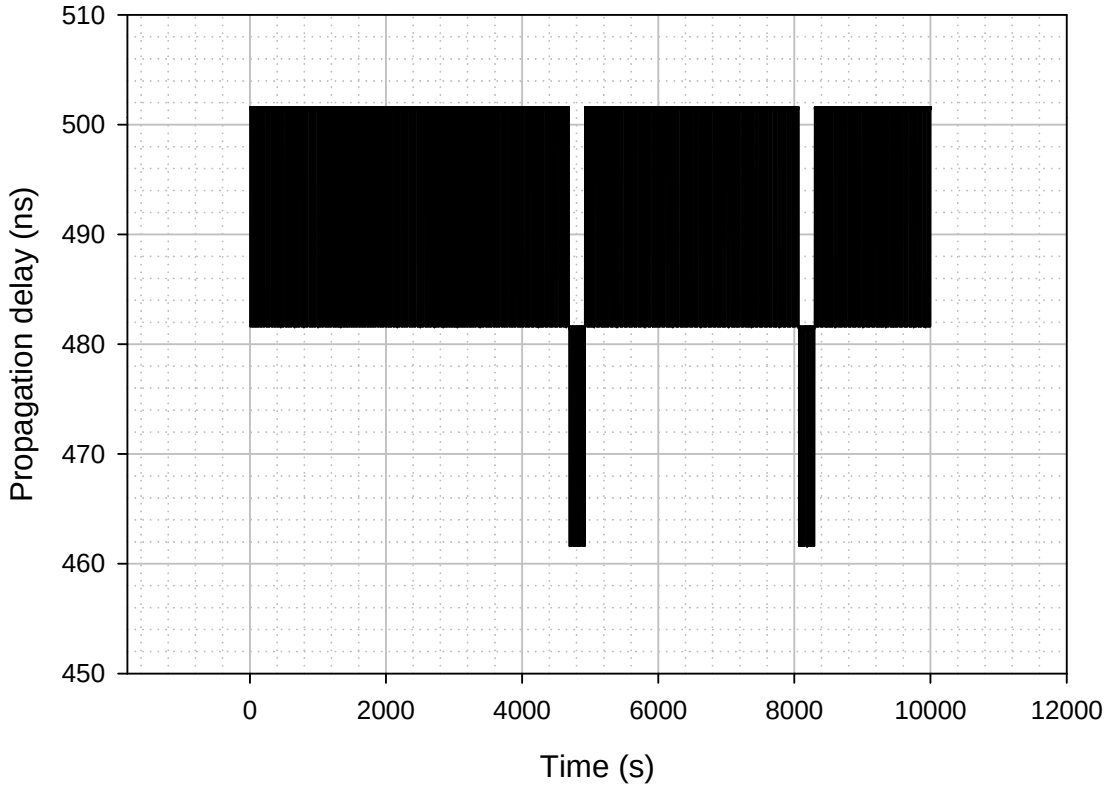


Case 2-01, Node 2 Results – 1

- Case 2 differs from case 1 in that the frequency tolerance of each node is ±5 ppm instead of ±100 ppm
  - The intent was to see the effect of small but nonzero frequency offsets
- As in case 1-01, the filtered and unfiltered phase at node 2 and the node 1 to node 2 propagation delay show 20 ns phase jumps
  - However, now the period is greater than 1000 s
    - The actual value of the period is not clear from the results, as the simulation time was 10010 s
- As in case 1-01, the steady-state peak-to-peak total unfiltered phase error is approximately 100 ns
- As in case 1-01, the steady-state peak-to-peak total filtered phase error is approximately 20 ns
  - The peak-to-peak phase variation between the 20 ns phase jumps is approximately 0.31 ns
  - The 0.01 Hz endpoint filter removes the fast variation, but the slow variation of magnitude 20 ns, due to the propagation time, remains

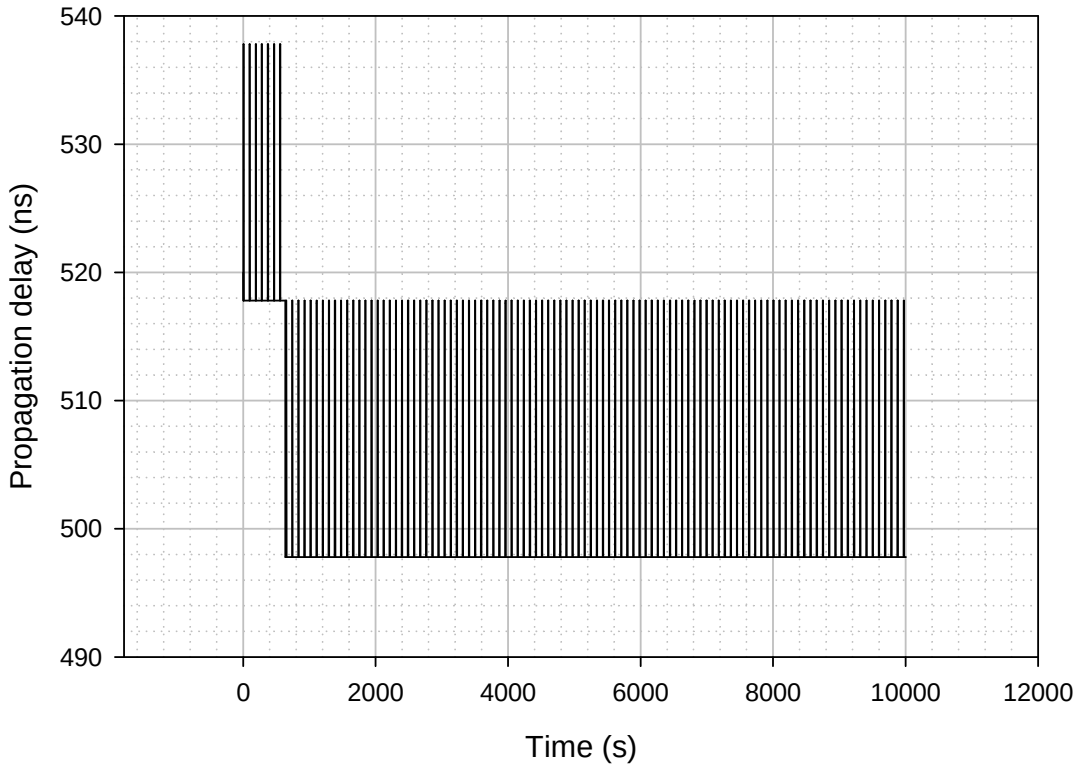
Case 2-01, Node 2 to 3 Propagation Delay

Case 2-01,Node 2 to 3 propagation delay
(after initialization)
Sync Interval = 0.01 s
Pdelay Interval = 0.1 s
Endpoint filter BW = 0.01 Hz
Local oscillator tolerance = +/- 5 ppm
(frequency offsets initialized randomly within tolerance range)



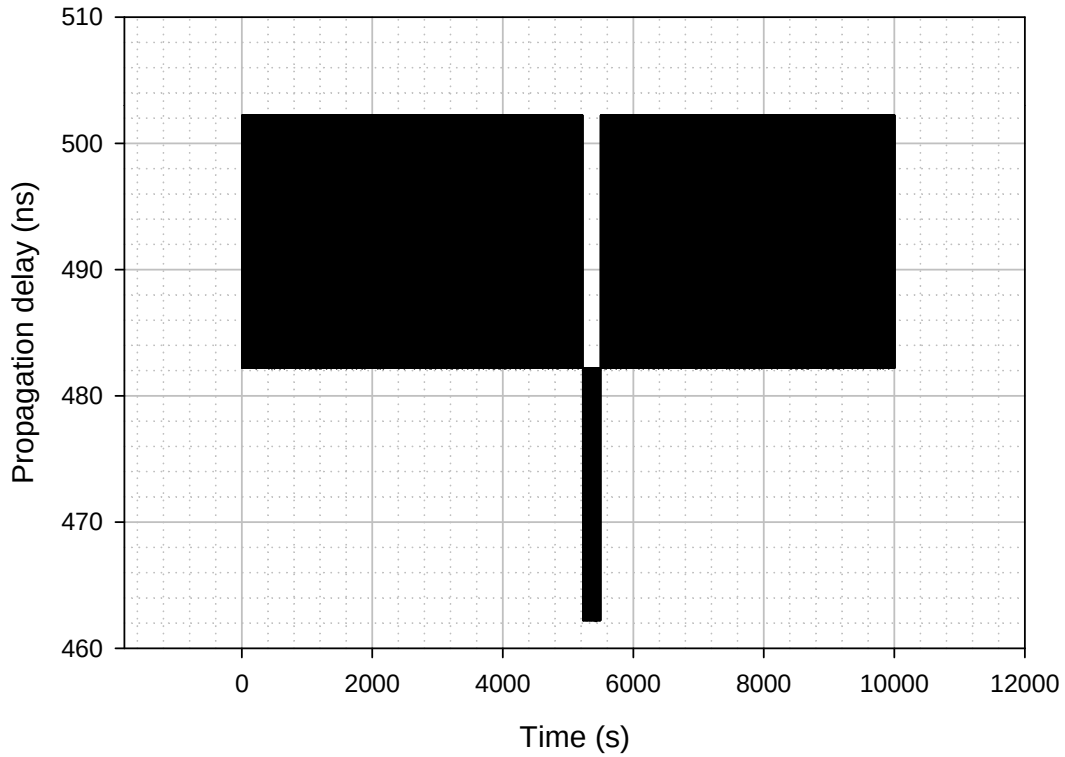
Case 2-01, Node 3 to 4 Propagation Delay

Case 2-01,Node 3 to 4 propagation delay
(after initialization)
Sync Interval = 0.01 s
Pdelay Interval = 0.1 s
Endpoint filter BW = 0.01 Hz
Local oscillator tolerance = +/- 5 ppm
(frequency offsets initialized randomly within tolerance range)



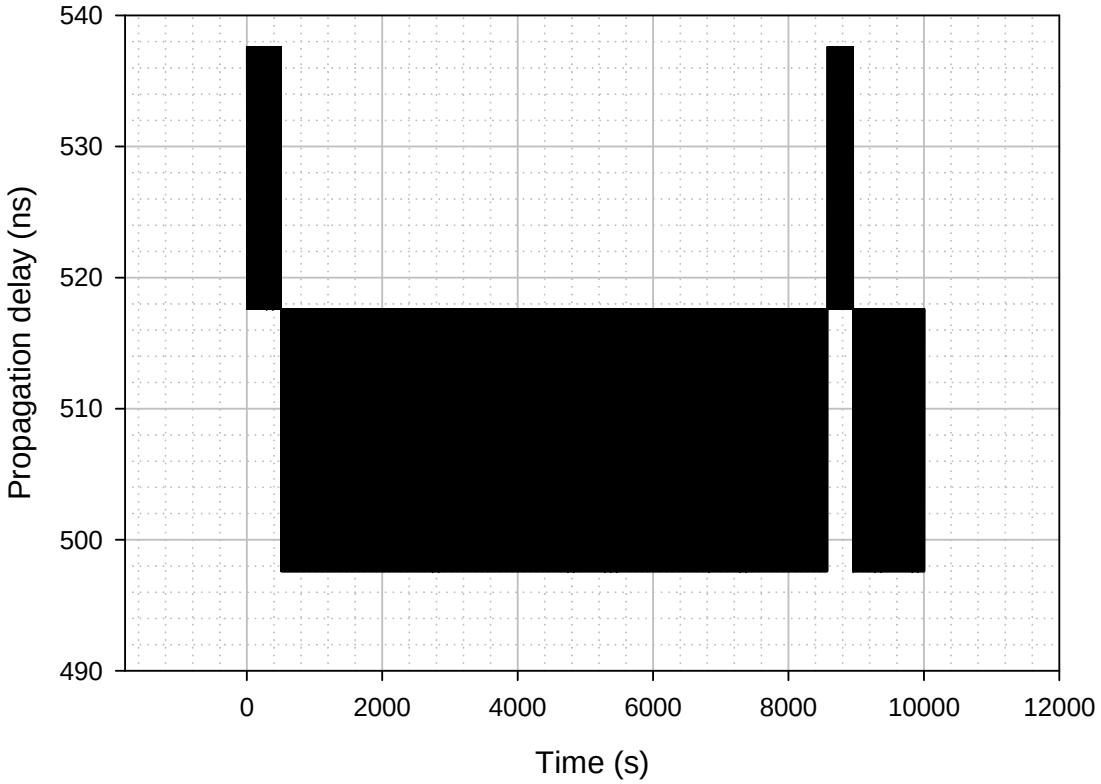
Case 2-01, Node 4 to 5 Propagation Delay

Case 2-01,Node 4 to 5 propagation delay
(after initialization)
Sync Interval = 0.01 s
Pdelay Interval = 0.1 s
Endpoint filter BW = 0.01 Hz
Local oscillator tolerance = +/- 5 ppm
(frequency offsets initialized randomly within tolerance range)



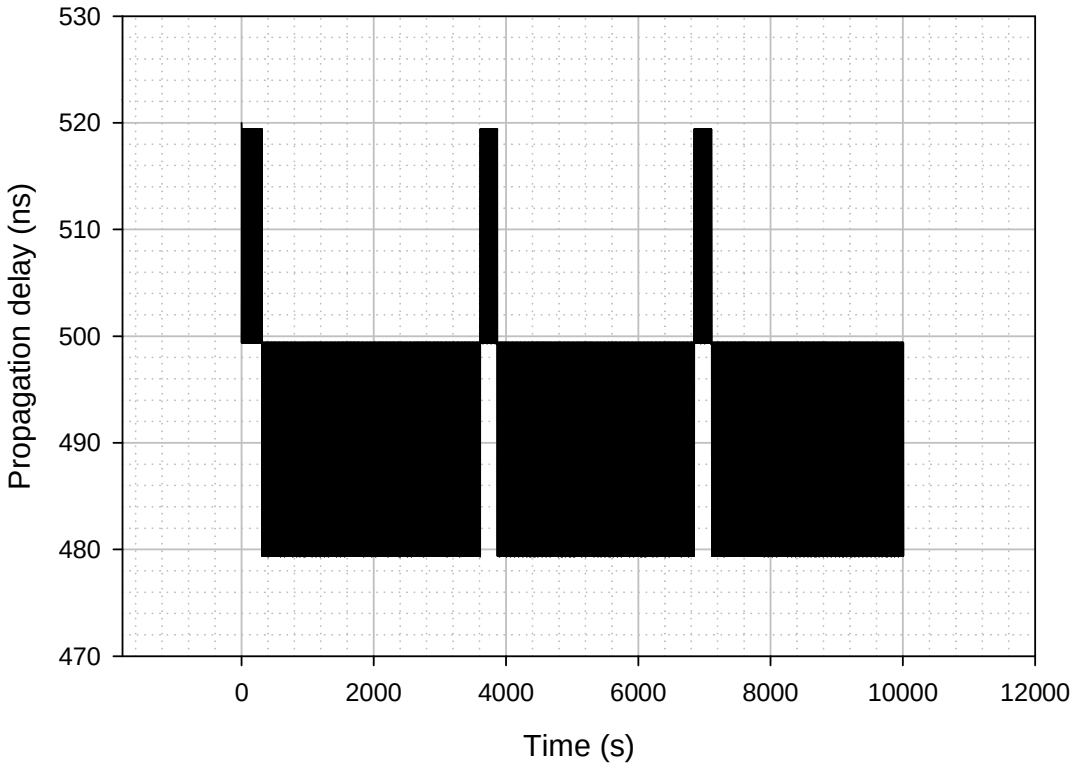
Case 2-01, Node 5 to 6 Propagation Delay

Case 2-01,Node 5 to 6 propagation delay
(after initialization)
Sync Interval = 0.01 s
Pdelay Interval = 0.1 s
Endpoint filter BW = 0.01 Hz
Local oscillator tolerance = +/- 5 ppm
(frequency offsets initialized randomly within tolerance range)



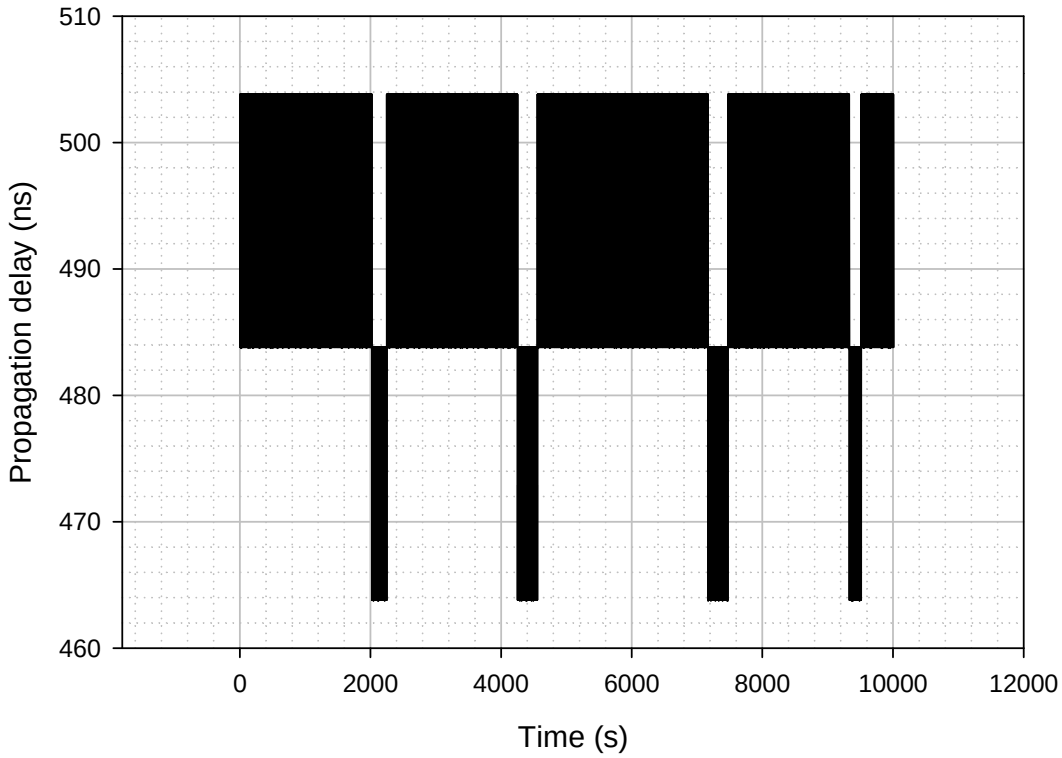
Case 2-01, Node 6 to 7 Propagation Delay

Case 2-01,Node 6 to 7 propagation delay
(after initialization)
Sync Interval = 0.01 s
Pdelay Interval = 0.1 s
Endpoint filter BW = 0.01 Hz
Local oscillator tolerance = +/- 5 ppm
(frequency offsets initialized randomly within tolerance range)



Case 2-01, Node 7 to 8 Propagation Delay

Case 2-01,Node 7 to 8 propagation delay
(after initialization)
Sync Interval = 0.01 s
Pdelay Interval = 0.1 s
Endpoint filter BW = 0.01 Hz
Local oscillator tolerance = +/- 5 ppm
(frequency offsets initialized randomly within tolerance range)

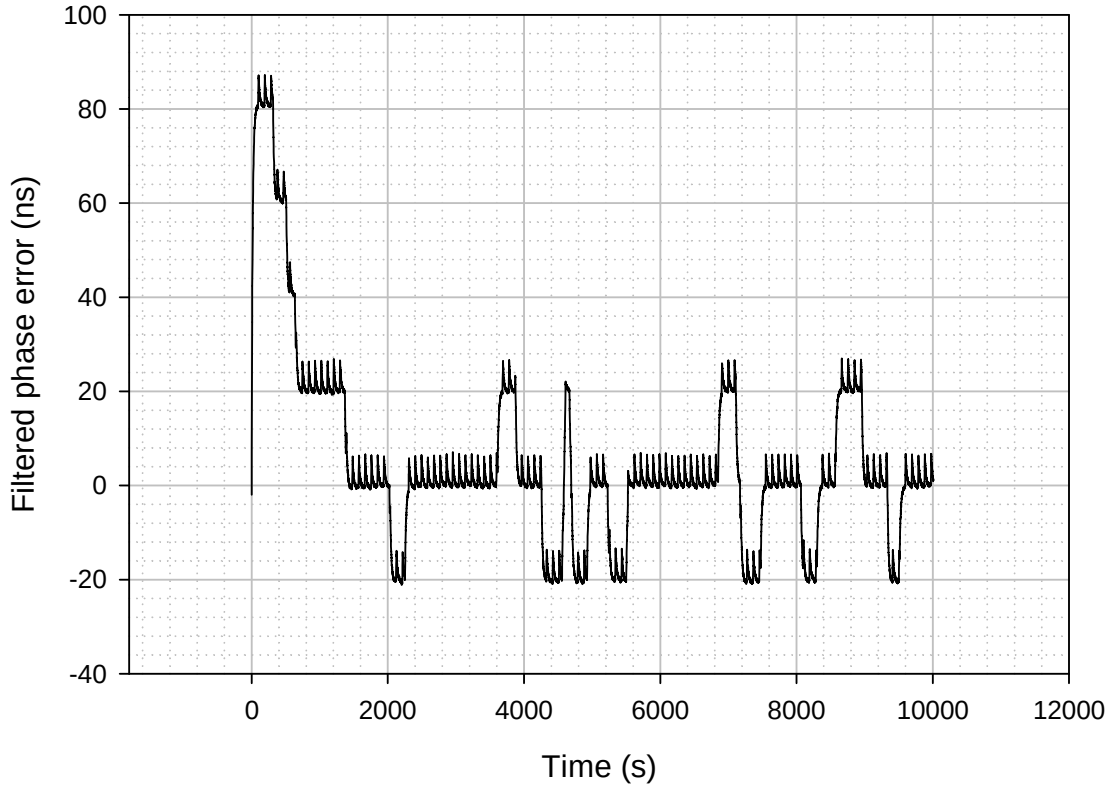


Case 2-01, Propagation Delay Results

- The preceding slides show that the propagation delays between successive nodes in case 2-01 experience 20 ns phase jumps with various periods
  - The periods range from approximately 2000 s to greater than 10000 s

Case 2-01, Node 8 – Filtered Phase Error

Case 2-01,Node 8
Filtered phase error
Sync Interval = 0.01 s
Pdelay Interval = 0.1 s
Endpoint filter BW = 0.01 Hz
Local oscillator tolerance = +/- 5 ppm
(frequency offsets initialized randomly within tolerance range)

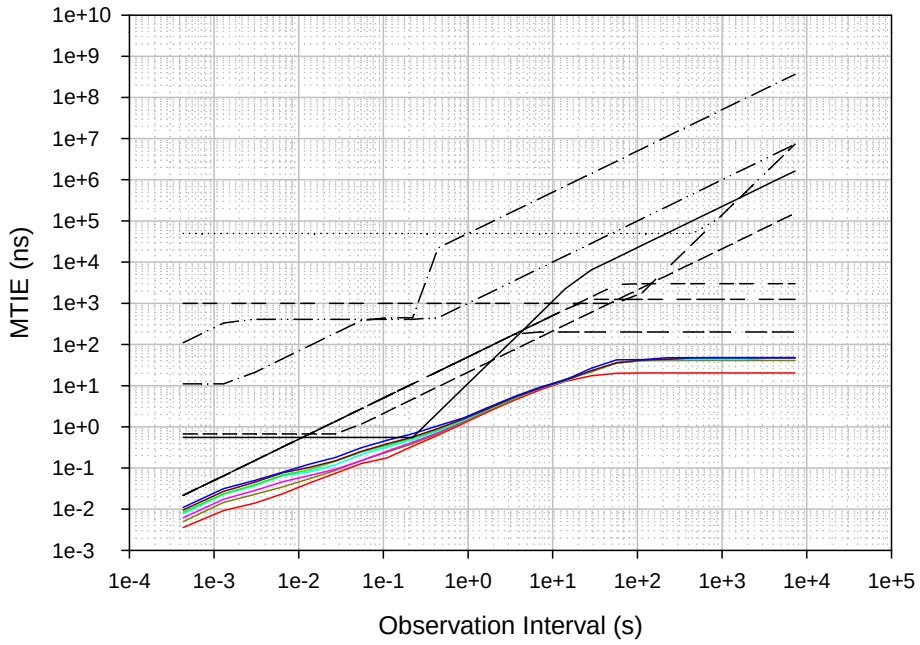


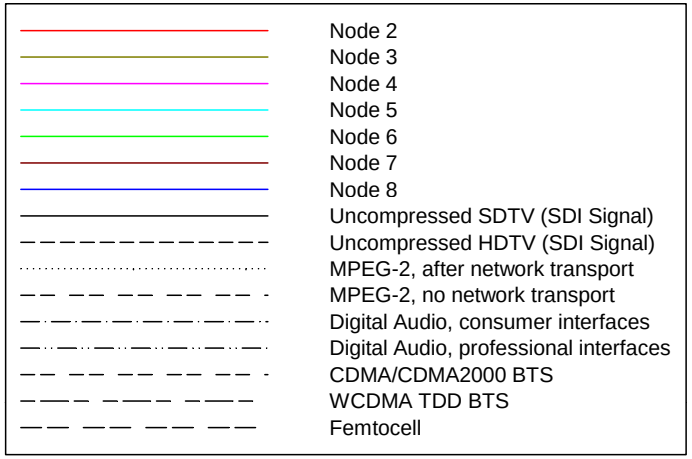
Case 2-01, Node 8 Filtered Phase Error Results

- The node 8 filtered phase error shows the cumulative effect of 20 ns phase jumps in the propagation delays between the successive nodes, and the residence times in the intermediate nodes
- In some cases, the phase jumps are sufficiently close together in time that the filtering reduces the magnitude to less than 20 ns
- The peak-to-peak phase variation is approximately 44 ns after the initial phase transient
  - It is actually not clear whether the initial phase excursion should be considered a transient; one possible way of determining this would be to run the simulation for a longer time and see if comparable phase excursions occur in the future

Case 2-01, Filtered Phase Error MTIE

Case 2-01, MTIE - unfiltered phase error
Sync Interval = 0.01 s
Pdelay Interval = 0.1 s
Endpoint filter BW = 0.01 Hz
Local oscillator tolerance = +/- 5 ppm
(frequency offsets initialized randomly within tolerance range)



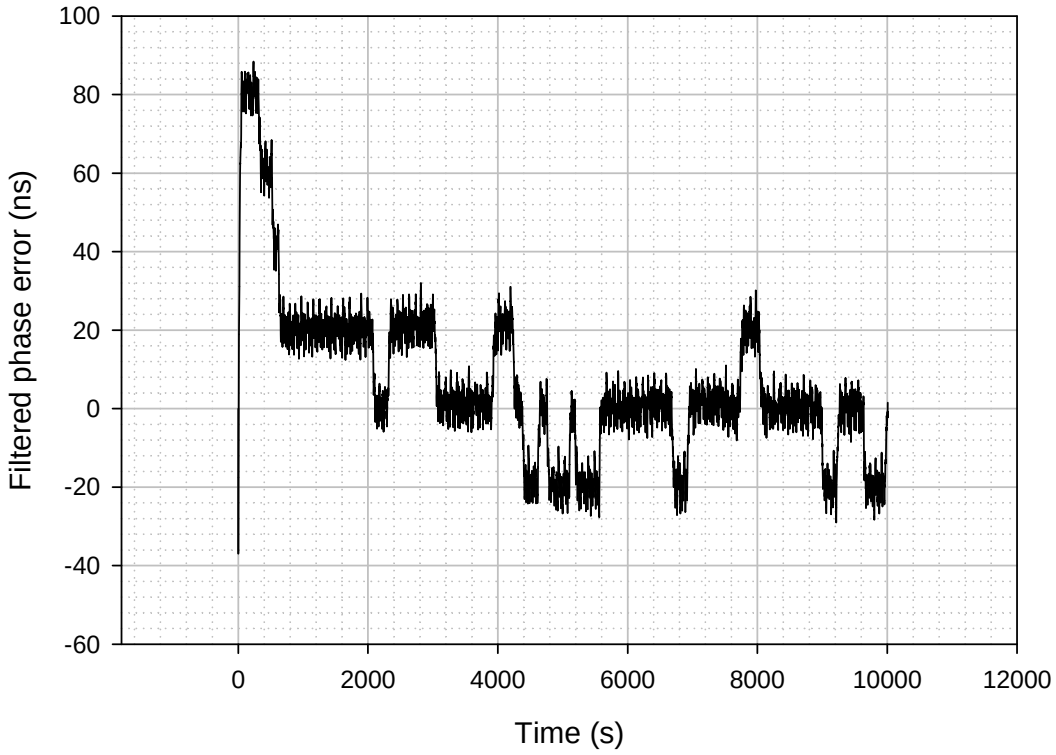


Case 2-01, Node 1 – 8 Jitter and Wander (MTIE) Results

- The initial transient (initial 1000 s) is excluded from the MTIE computation
- As in case 1-01, all the requirements are met by the filtered phase at the egress of each node, with the exception of the uncompressed standard definition (SDI video) signal
- The filtered phase meets the uncompressed standard definition video signal requirement at nodes 2 – 6, but exceeds it at nodes 7 and 8(just barely at node 7)
- The filtered phase MTIE results are slightly less than the corresponding results for case 1-01 for observation intervals between 0.1 s and 1.0 s
- The long-term MTIE results are slightly more than the corresponding results for case 1-01
  - As indicated earlier, it is not clear whether the initial large phase excursion should be considered a transient; a longer simulation time could indicate if similar excursions occur in the future

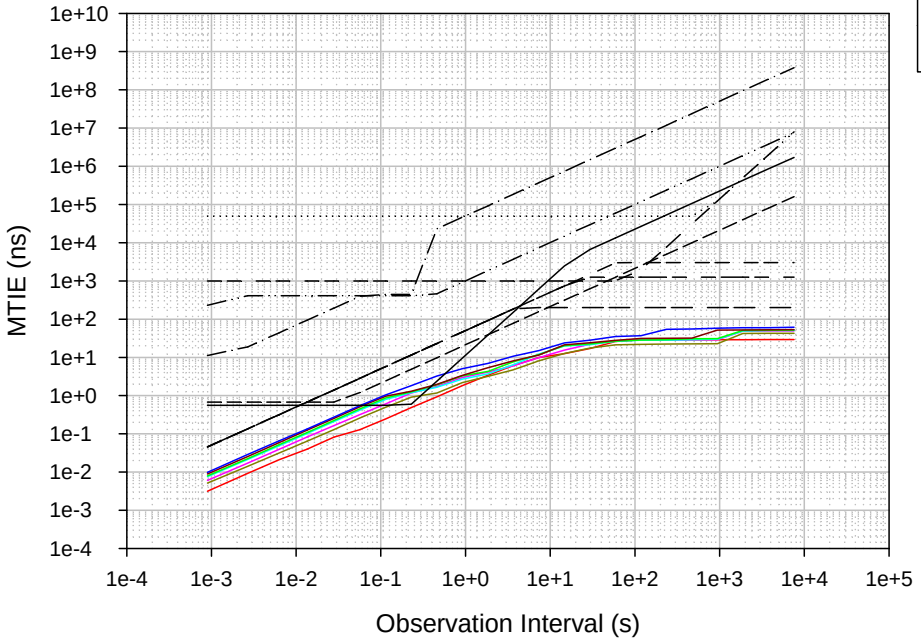
Case 2-125, Node 8 – Filtered Phase Error

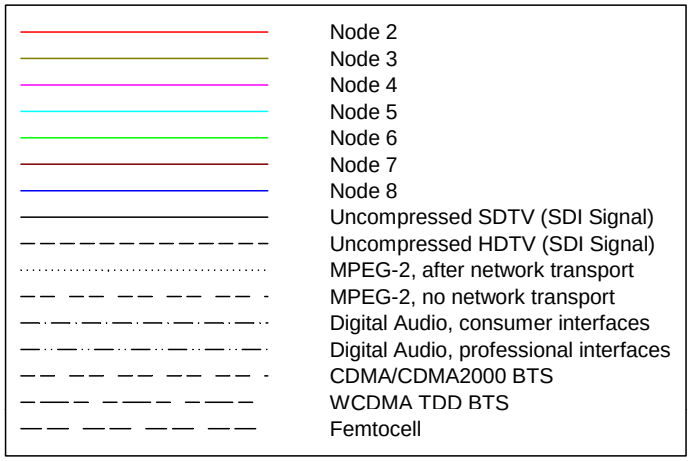
Case 2-125,Node 8
Filtered phase error
Sync Interval = 0.125 s
Pdelay Interval = 1.0 s
Endpoint filter BW = 0.01 Hz
Local oscillator tolerance = +/- 5 ppm
(frequency offsets initialized randomly within tolerance range)



Case 2-125, Filtered Phase Error MTIE

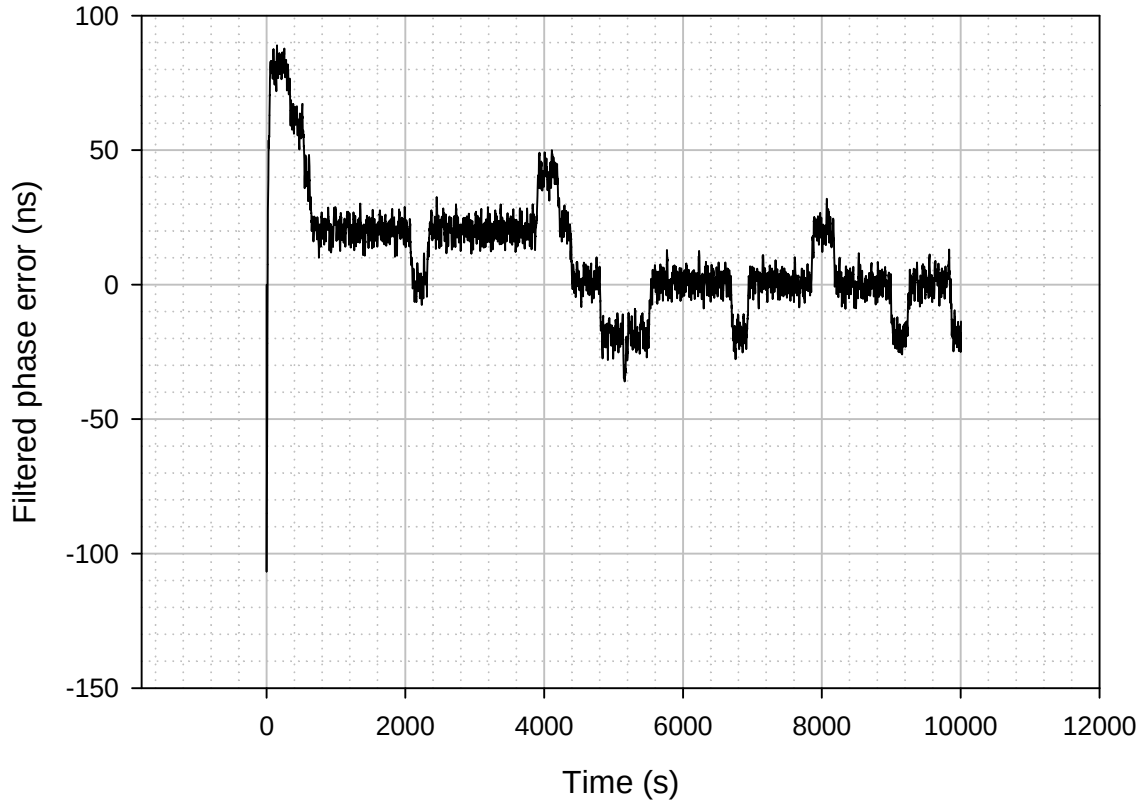
Case 2-125, MTIE - unfiltered phase error
Sync Interval = 0.125 s
Pdelay Interval = 1.0 s
Endpoint filter BW = 0.01 Hz
Local oscillator tolerance = +/- 5 ppm
(frequency offsets initialized randomly within tolerance range)





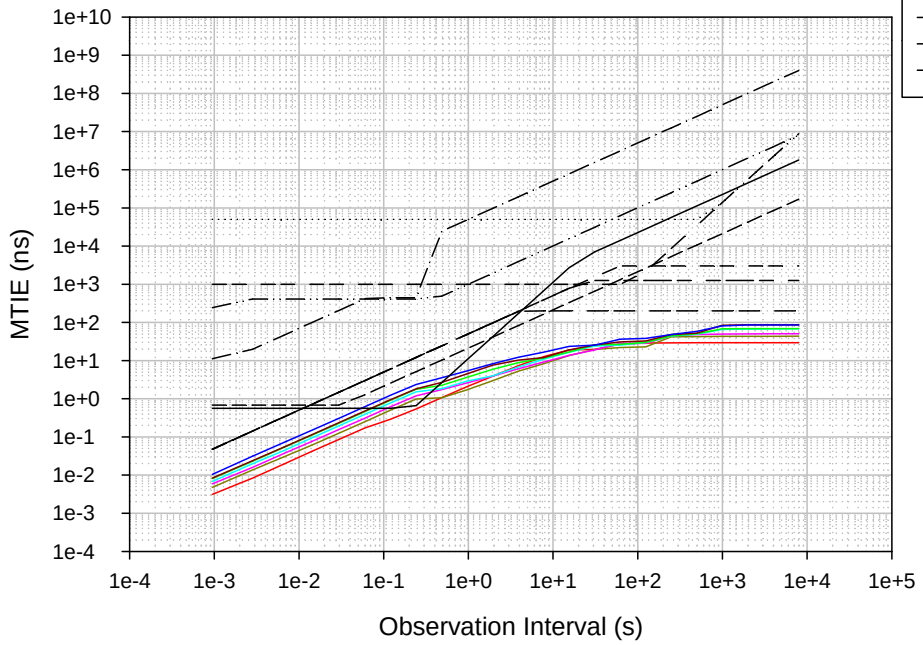
Case 2-250, Node 8 – Filtered Phase Error

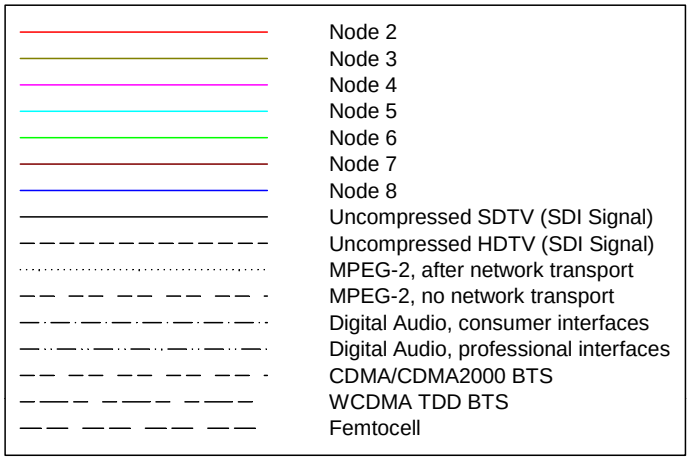
Case 2-250,Node 8
Filtered phase error
Sync Interval = 0.250 s
Pdelay Interval = 2.0 s
Endpoint filter BW = 0.01 Hz
Local oscillator tolerance = +/- 5 ppm
(frequency offsets initialized randomly within tolerance range)



Case 2-250, Filtered Phase Error MTIE

Case 2-250, MTIE - unfiltered phase error
Sync Interval = 0.250 s
Pdelay Interval = 2.0 s
Endpoint filter BW = 0.01 Hz
Local oscillator tolerance = +/- 5 ppm
(frequency offsets initialized randomly within tolerance range)





Cases 2-125 and 2-250, Node 1 – 8 Jitter and Wander (MTIE) Results - 1

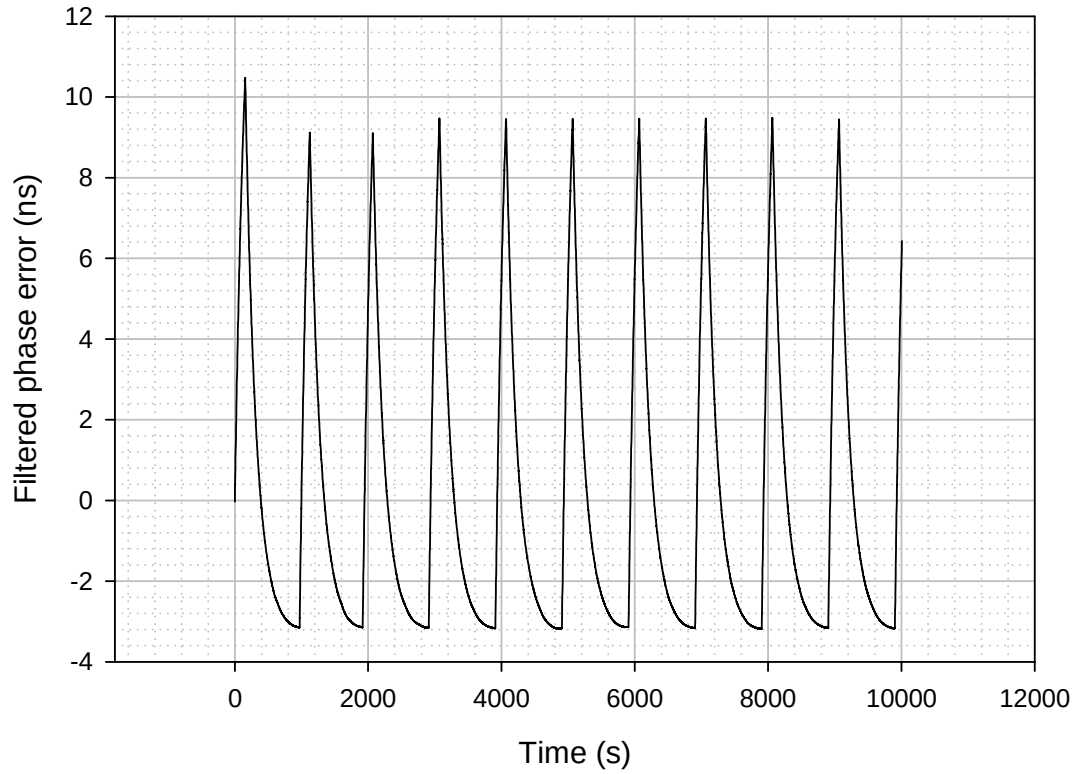
- Detailed results for case 1-250 (0.250 s sync interval, 2.0 s Pdelay interval) are contained in backup material
- MTIE results are very similar to case 2-01
- The initial transient (initial 1000 s) is excluded from the MTIE computation; as indicated earlier, it is not clear whether this initial large phase excursion should be considered a transient
  - a longer simulation time could indicate if similar excursions occur in the future
- As in cases 1-01, 1-125, 1-250, and 2-01, all the requirements are met by the filtered phase at the egress of each node, with the exception of the uncompressed standard definition (SDI video) signal
- The filtered phase meets the uncompressed standard definition video signal requirement at node 2, but exceeds it at nodes 3 – 8
- The filtered phase MTIE results are slightly above the corresponding results for case 2-01

Cases 2-125 and 2-250, Node 1 – 8 Jitter and Wander (MTIE) Results - 1

- The filtered phase MTIE results are slightly less than the corresponding results for cases 1-125 and 1-250, respectively, for observation intervals less than approximately 1.0 s, and slightly more than the corresponding results for cases 1-125 and 1-250, respectively, for longer observation intervals
- **As in the case 1 subcases, the results are not appreciably different when the sync interval is increased to 0.250 s and the Pdelay interval to 2.0 s, compared to cases 1-01 and 1-125**
  - The meeting or not meeting of the requirements is the same in all subcases

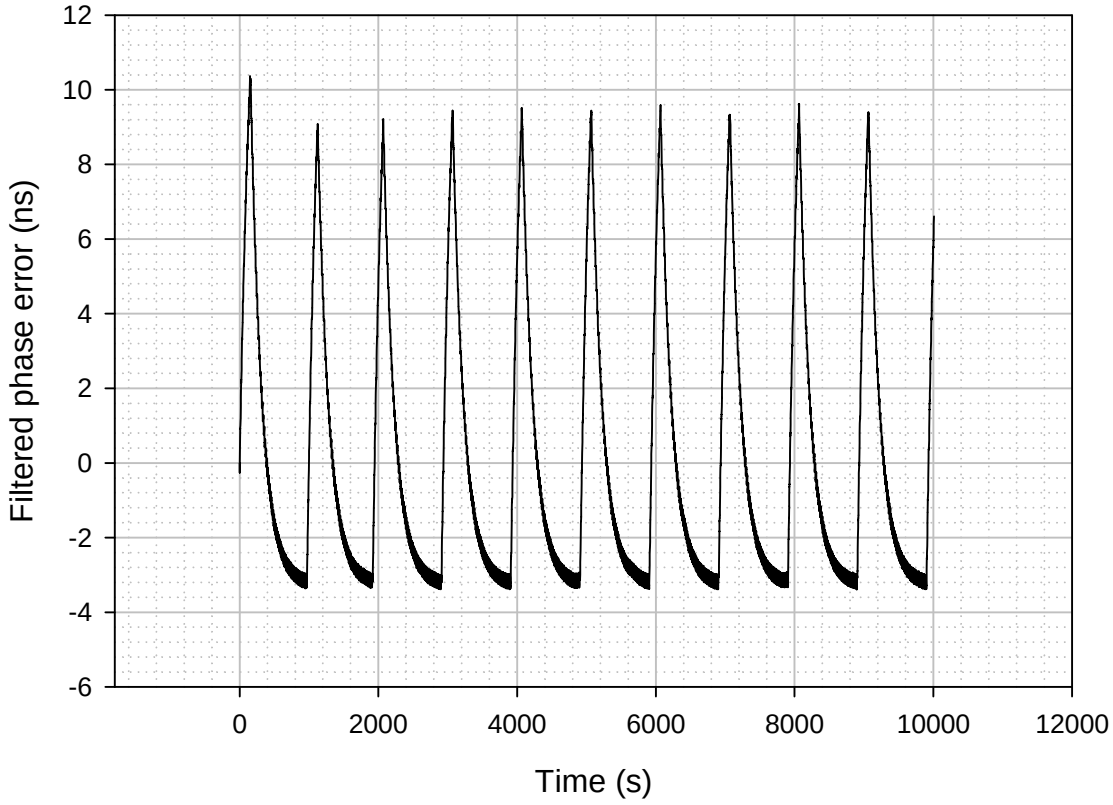
Case 3-01, Node 2 – Filtered Phase Error

Case 3-01,Node 2
Filtered phase error
Sync Interval = 0.01 s
Pdelay Interval = 0.1 s
Endpoint filter BW = 0.001 Hz
Local oscillator tolerance = +/- 100 ppm
(frequency offsets initialized randomly within tolerance range)



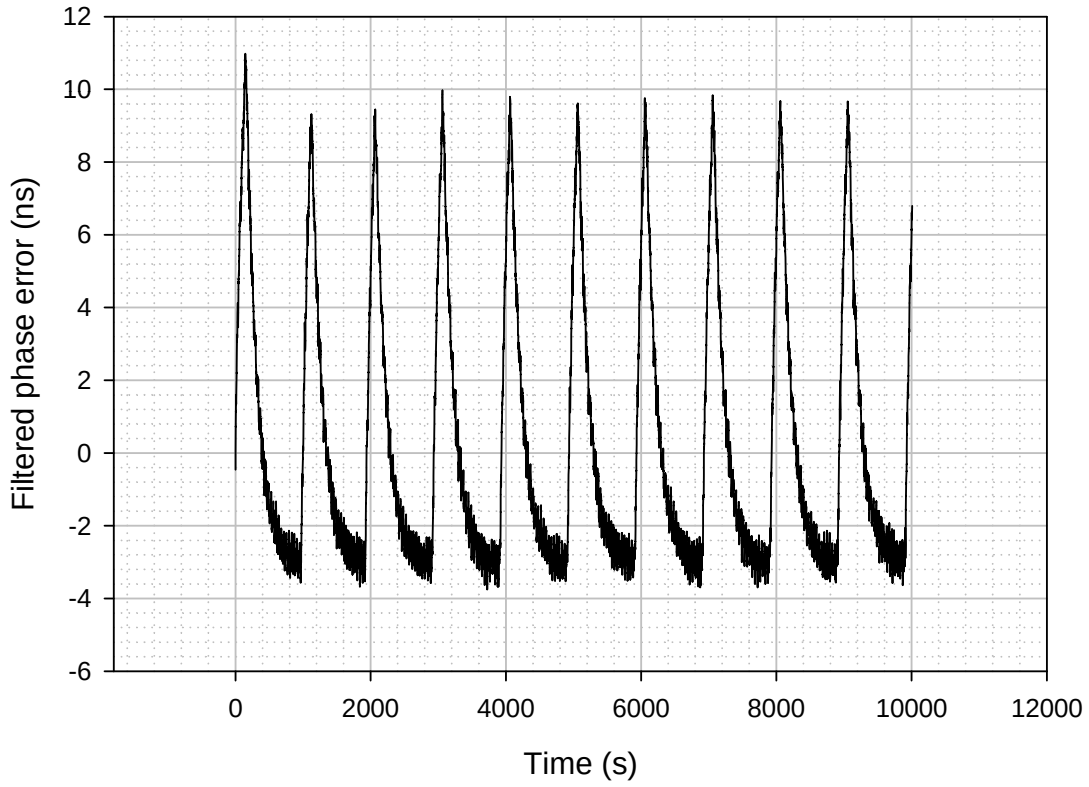
Case 3-01, Node 3 – Filtered Phase Error

Case 3-01,Node 3
Filtered phase error
Sync Interval = 0.01 s
Pdelay Interval = 0.1 s
Endpoint filter BW = 0.001 Hz
Local oscillator tolerance = +/- 100 ppm
(frequency offsets initialized randomly within tolerance range)



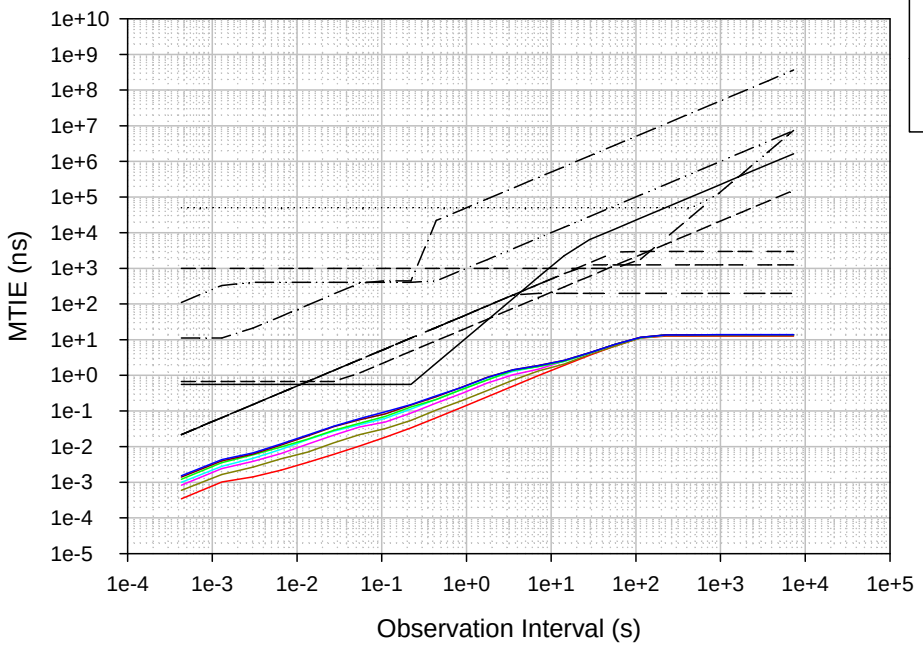
Case 3-01, Node 8 – Filtered Phase Error

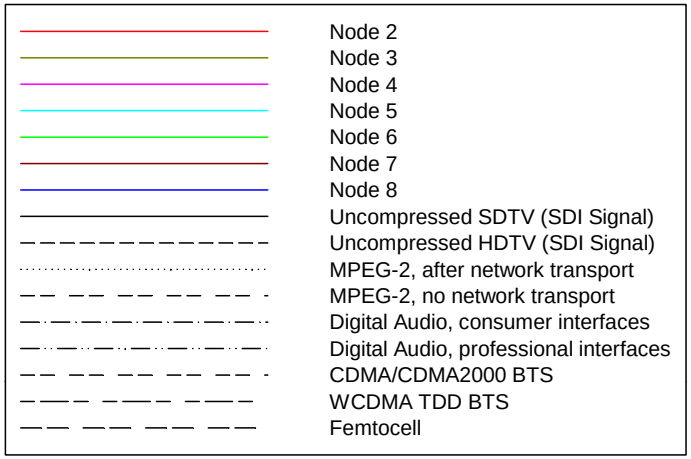
Case 3-01,Node 8
Filtered phase error
Sync Interval = 0.01 s
Pdelay Interval = 0.1 s
Endpoint filter BW = 0.001 Hz
Local oscillator tolerance = +/- 100 ppm
(frequency offsets initialized randomly within tolerance range)



Case 3-01, Filtered Phase Error MTIE

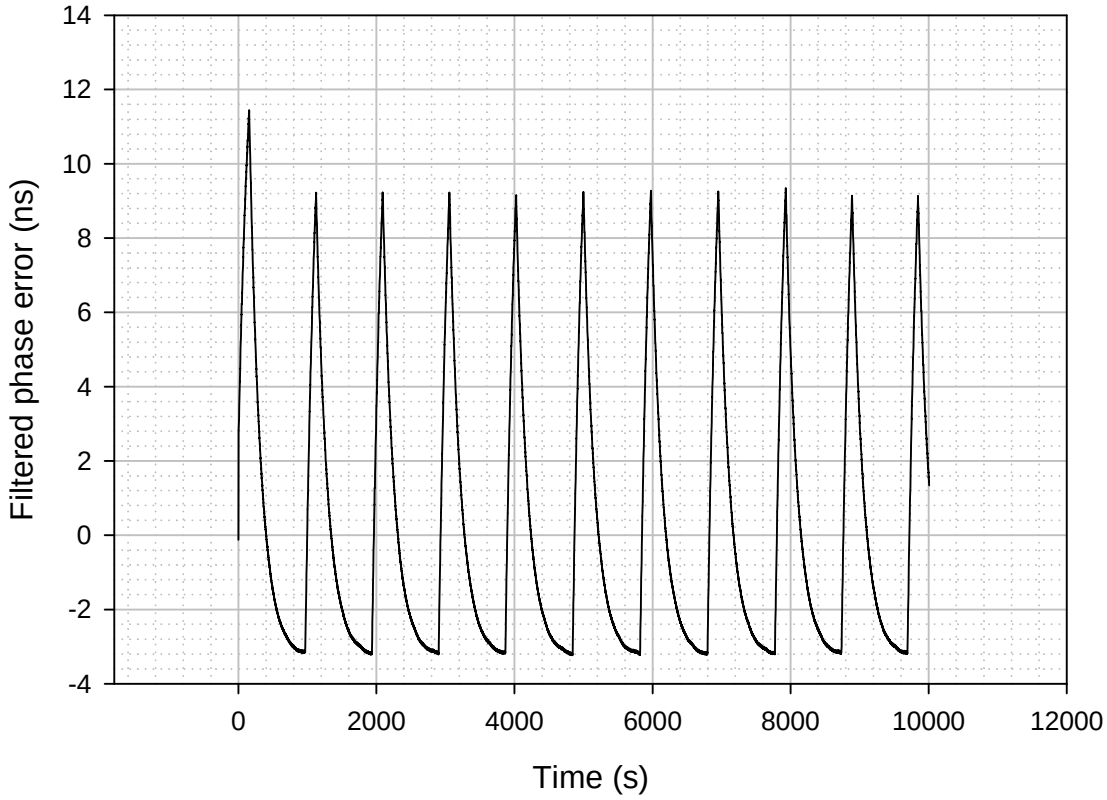
Case 3-01, MTIE - unfiltered phase error
Sync Interval = 0.01 s
Pdelay Interval = 0.1 s
Endpoint filter BW = 0.001 Hz
Local oscillator tolerance = +/- 100 ppm
(frequency offsets initialized randomly within tolerance range)





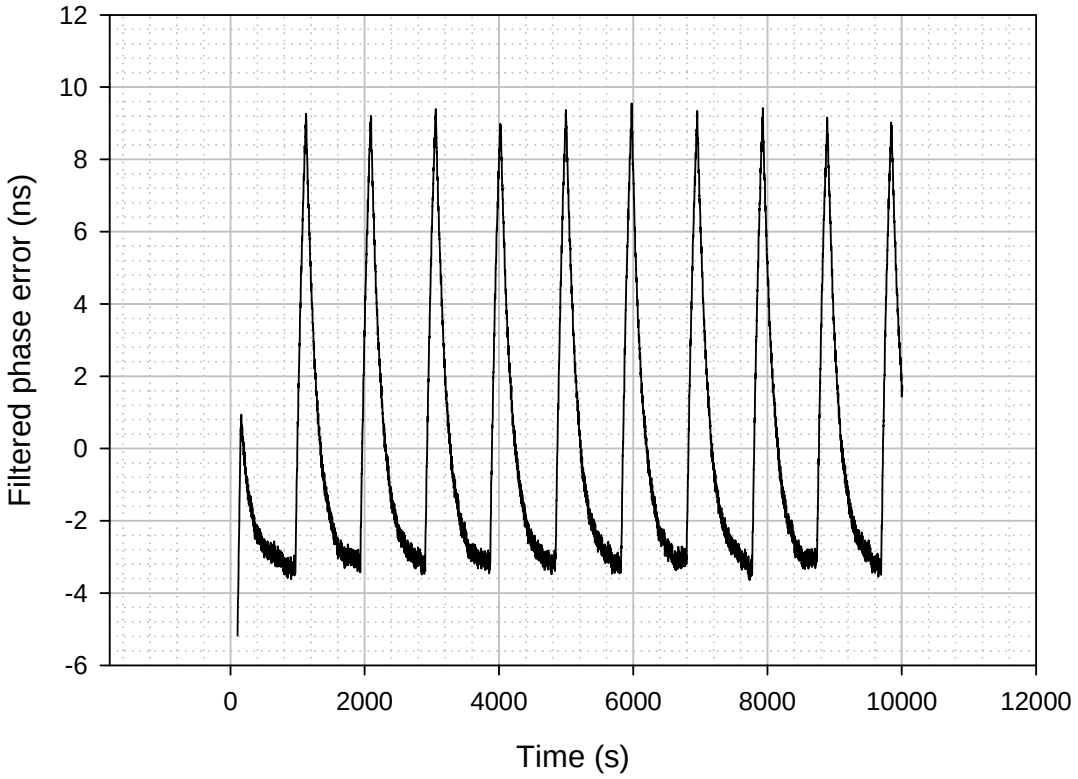
Case 3-125, Node 2 – Filtered Phase Error

Case 3-125,Node 2
Filtered phase error
Sync Interval = 0.125 s
Pdelay Interval = 1.0 s
Endpoint filter BW = 0.001 Hz
Local oscillator tolerance = +/- 100 ppm
(frequency offsets initialized randomly within tolerance range)



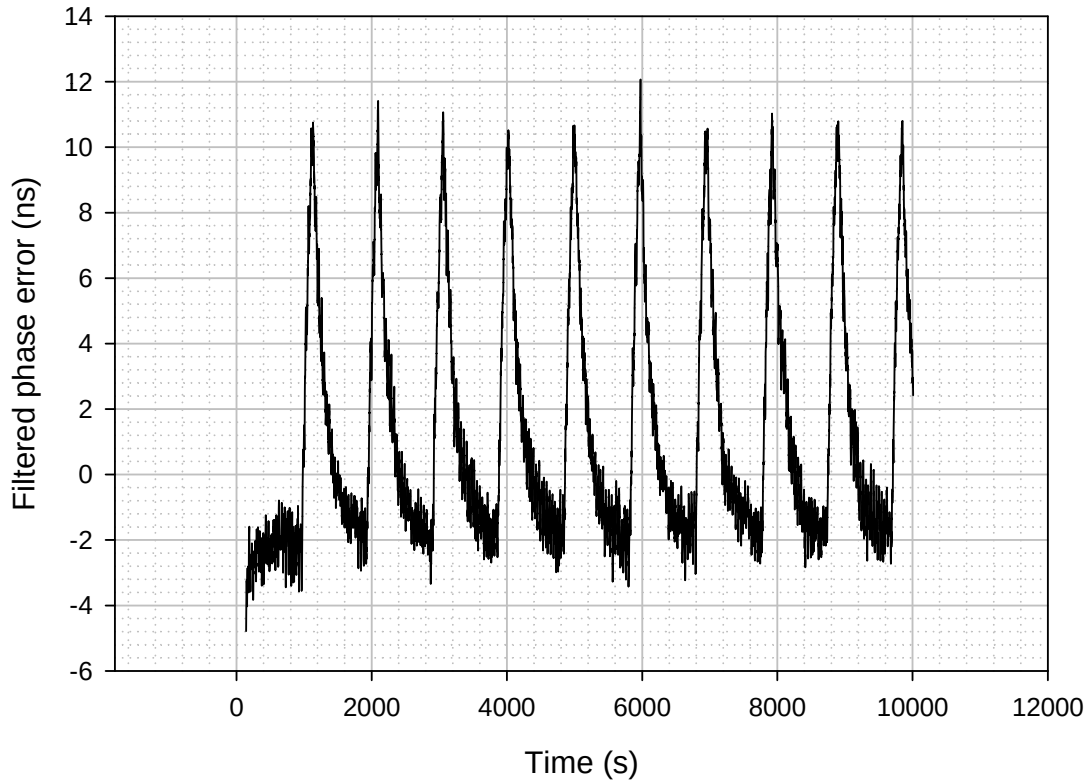
Case 3-125, Node 3 – Filtered Phase Error

Case 3-125,Node 3
Filtered phase error (initial transient removed)
Sync Interval = 0.125 s
Pdelay Interval = 1.0 s
Endpoint filter BW = 0.001 Hz
Local oscillator tolerance = +/- 100 ppm
(frequency offsets initialized randomly within tolerance range)



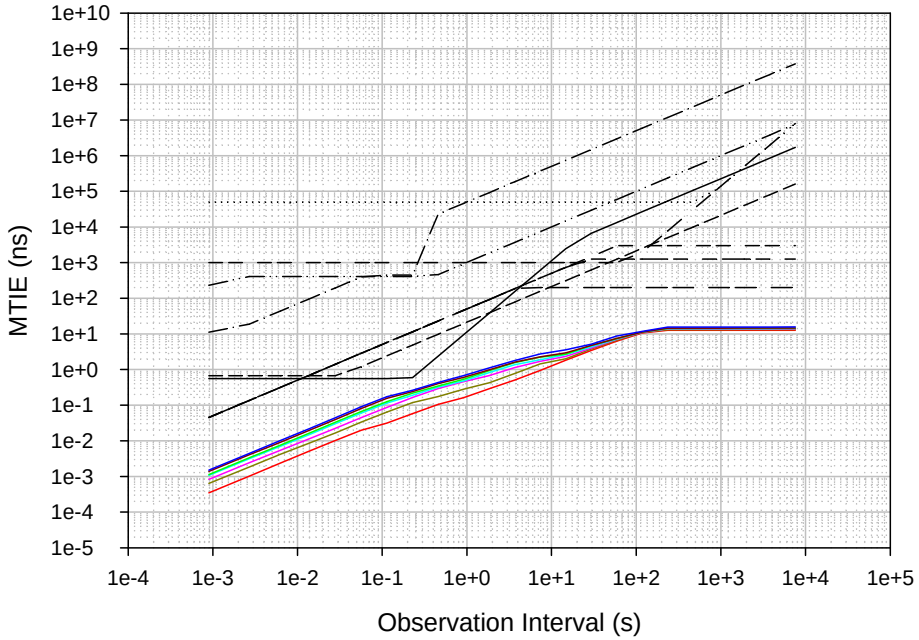
Case 3-125, Node 8 – Filtered Phase Error

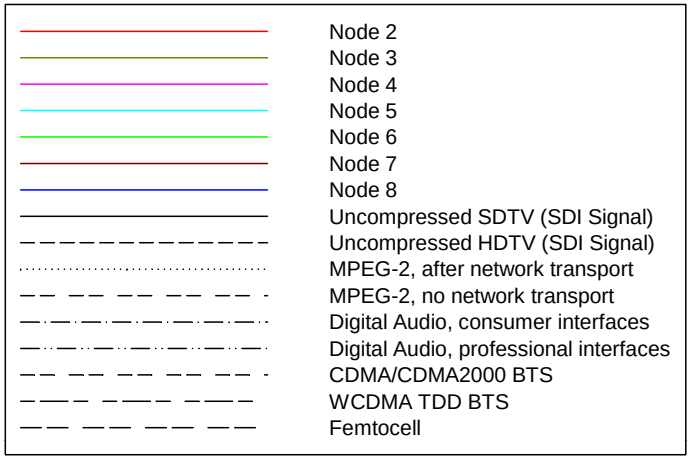
Case 3-125,Node 8
Filtered phase error (initial transient removed)
Sync Interval = 0.125 s
Pdelay Interval = 1.0 s
Endpoint filter BW = 0.001 Hz
Local oscillator tolerance = +/- 100 ppm
(frequency offsets initialized randomly within tolerance range)



Case 3-125, Filtered Phase Error MTIE

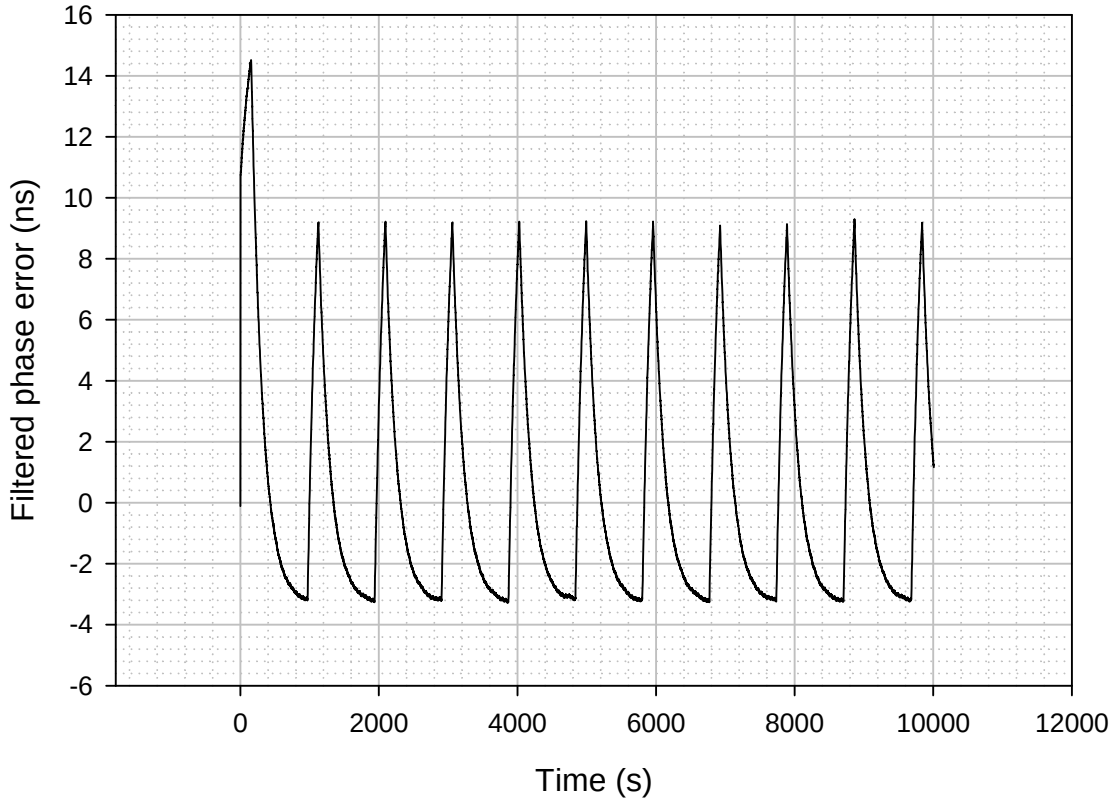
Case 3-125, MTIE - unfiltered phase error
Sync Interval = 0.125 s
Pdelay Interval = 1.0 s
Endpoint filter BW = 0.001 Hz
Local oscillator tolerance = +/- 100 ppm
(frequency offsets initialized randomly within tolerance range)





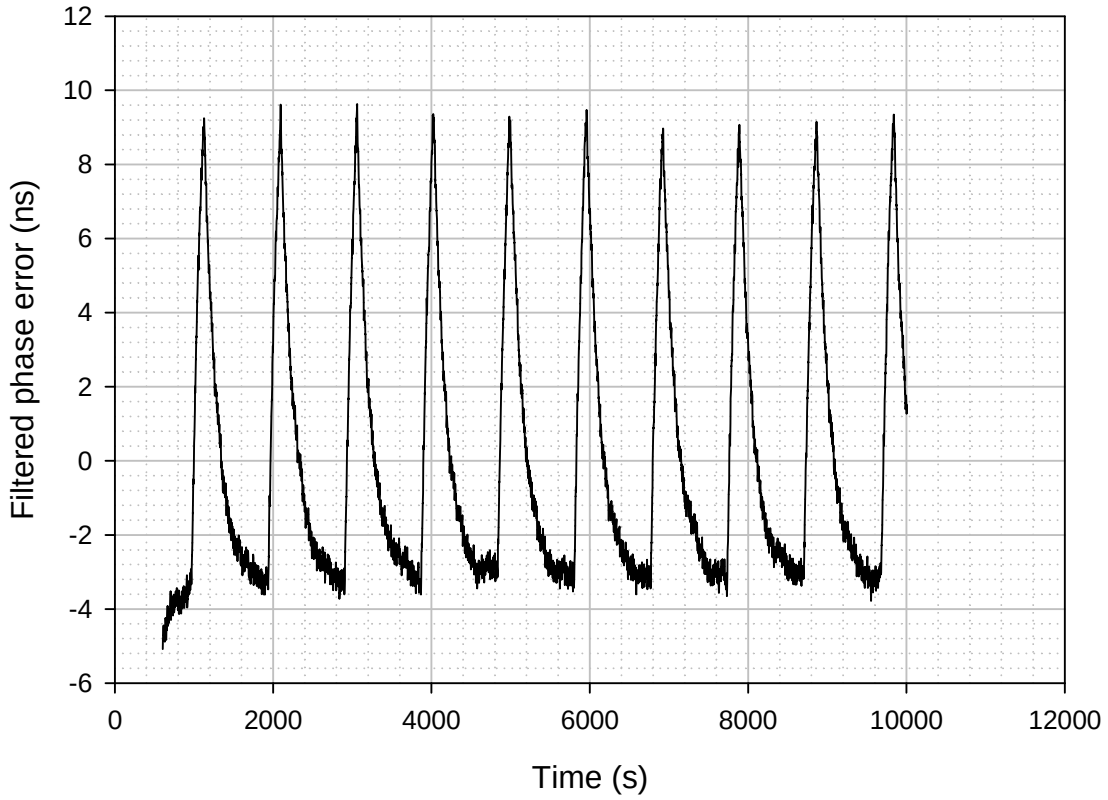
Case 3-250, Node 2 – Filtered Phase Error

Case 3-250,Node 2
Filtered phase error
Sync Interval = 0.250 s
Pdelay Interval = 2.0 s
Endpoint filter BW = 0.001 Hz
Local oscillator tolerance = +/- 100 ppm
(frequency offsets initialized randomly within tolerance range)



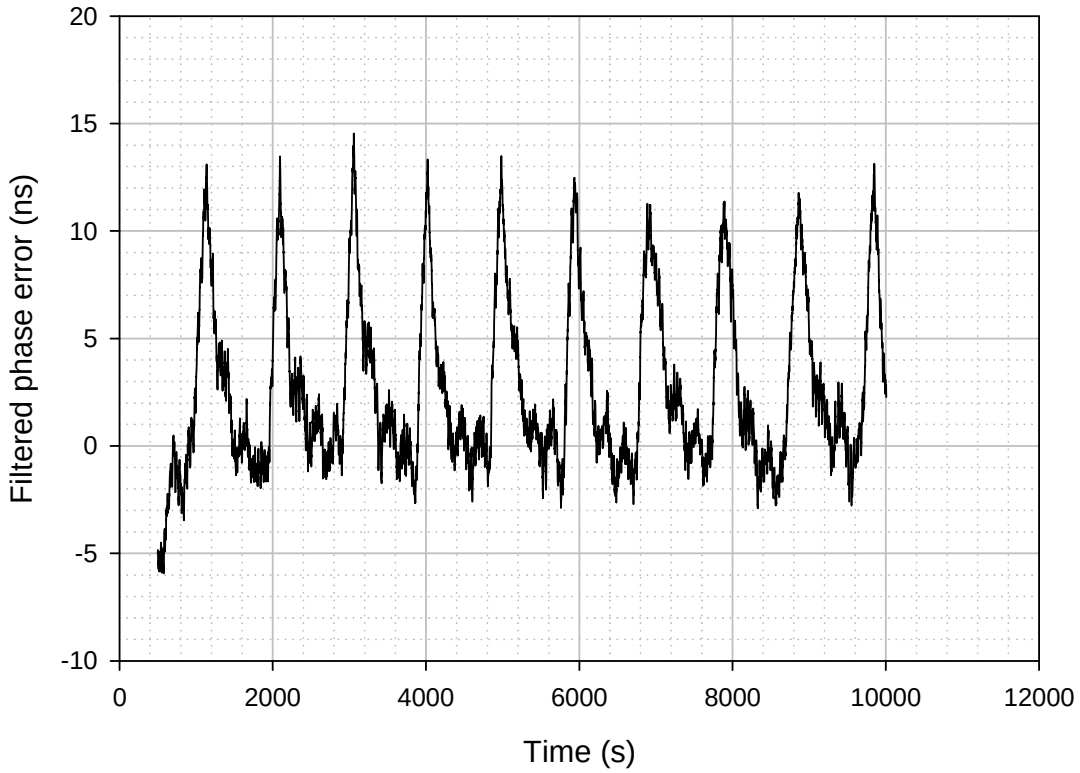
Case 3-250, Node 3 – Filtered Phase Error

Case 3-250,Node 3
Filtered phase error, initial transient removed
Sync Interval = 0.250 s
Pdelay Interval = 2.0 s
Endpoint filter BW = 0.001 Hz
Local oscillator tolerance = +/- 100 ppm
(frequency offsets initialized randomly within tolerance range)



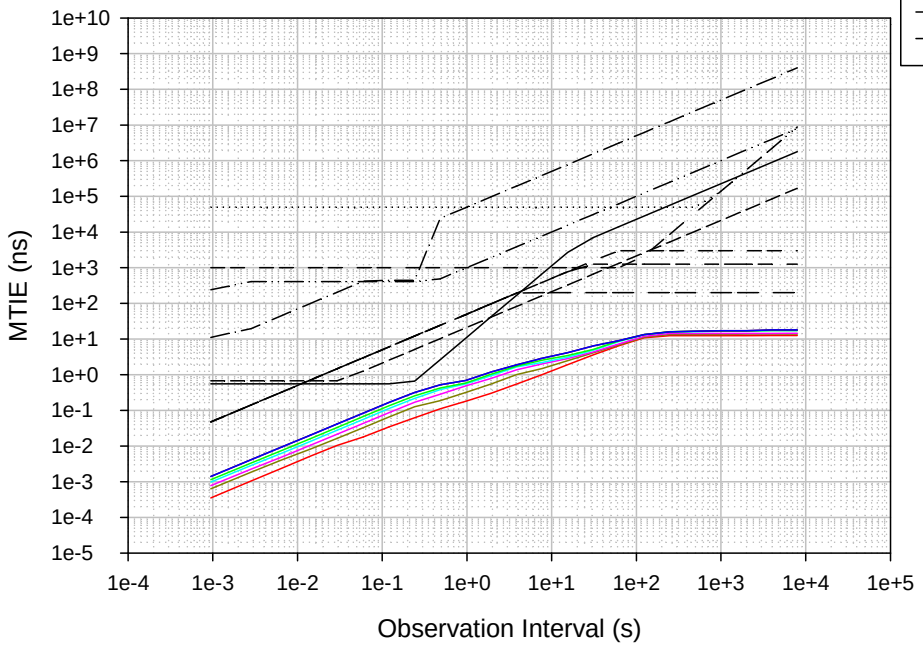
Case 3-250, Node 8 – Filtered Phase Error

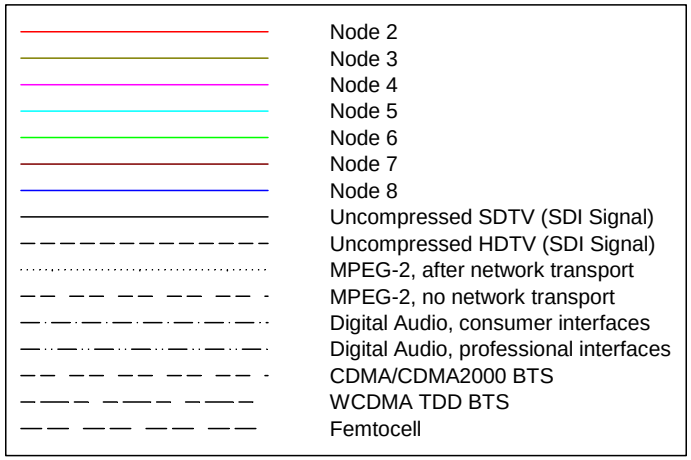
Case 3-250,Node 8
Filtered phase error, initial transient removed
Sync Interval = 0.250 s
Pdelay Interval = 2.0 s
Endpoint filter BW = 0.001 Hz
Local oscillator tolerance = +/- 100 ppm
(frequency offsets initialized randomly within tolerance range)



Case 3-250, Filtered Phase Error MTIE

Case 3-250, MTIE - unfiltered phase error
Sync Interval = 0.250 s
Pdelay Interval = 2.0 s
Endpoint filter BW = 0.001 Hz
Local oscillator tolerance = +/- 100 ppm
(frequency offsets initialized randomly within tolerance range)





Cases 3-01, 3-125 and 2-250 Filtered Phase and Jitter/Wander (MTIE) Results - 1

- Case 3 differs from case 1 only in the filter bandwidth (0.001 Hz for case 3, versus 0.01 Hz for case 1)
  - Therefore, the results for unfiltered phase, propagation delay, residence time (and all other quantities that don't depend on the endpoint filter) are the same
  - It is only necessary to show results for filtered phase error and jitter/wander (MTIE)
- Filtered phase and MTIE results are very similar for the three cases
  - MTIE for cases 3-125 and 3-250 are slightly larger than for case 3-01, but all three cases meet the MTIE masks for all the applications
- **As in the case 1 subcases, the results are not appreciably different when the sync interval is increased to 0.250 s and the Pdelay interval to 2.0 s, compared to cases 1-01 and 1-125**

Cases 2-125 and 2-250, Node 1 – 8 Jitter and Wander (MTIE) Results - 1

- The filtered phase MTIE results are slightly less than the corresponding results for cases 1-125 and 1-250, respectively, for observation intervals less than approximately 1.0 s, and slightly more than the corresponding results for cases 1-125 and 1-250, respectively, for longer observation intervals
- **As in the case 1 subcases, the results are not appreciably different when the sync interval is increased to 0.250 s and the Pdelay interval to 2.0 s, compared to cases 1-01 and 1-125**
  - The meeting or not meeting of the requirements is the same in all subcases

Summary and Conclusions – 1

- Jitter/Wander accumulation simulation results have been presented based on current P802.1AS specifications
- Results have been presented for
  - Current assumptions for sync interval (0.01 s) and Pdelay interval (0.1 s)
  - Longer sync and Pdelay intervals
    - 0.125 s (sync) and 1.0 s (Pdelay)
    - 0.250 s (sync) and 2.0 s (Pdelay)
- Simulation cases have considered
  - Endpoint filter bandwidths of 0.01 Hz and 0.001 Hz
  - Full-range frequency tolerances (±100 ppm) and tighter tolerances (±5 ppm)
- Did not consider
  - Local clock/oscillator noise/instability
  - Variability in sync interval, Pdelay interval, Pdelay turnaround time, residence time, and PHY latency
  - Multiple replications to obtain statistics on MTIE

Summary and Conclusions – 2

- These initial results indicated
  - **No appreciable difference when the sync interval is increased to 0.125 s or 0.250 s, and the Pdelay interval to 1.0 s or 2.0 s, compared to the current assumptions of 0.01 s for sync interval and 0.1 s for Pdelay interval**
  - **Note that the above conclusion is for cases that ignored clock instability and drift**
    - **Depending on the magnitude of the drift, the sync interval, and the assumed model, the effect of clock instability and drift may or may not be significant**
  - **There can be low-frequency (long-period) phase jumps that are multiples of 20 ns, due to 40 ns phase measurement granularity**
    - A companion presentation [6] (to the current one) looks at the possibility of reducing the effect of this using propagation time averaging

Future Work

- The following items should be considered in future work
  - Local clock/oscillator noise/instability
    - Need assessment of whether current AVB assumption of 4 ppm/s maximum frequency drift rate is realistic and, if not, what a realistic maximum frequency drift rate would be (and some indication of the dynamics/assumed model for the frequency instability
  - Variability in sync interval, Pdelay interval, Pdelay turnaround time, residence time, and PHY latency
  - Multiple replications to obtain statistics on MTIE
  - Propagation time averaging (see [6] for initial consideration)

References – 1

1. Geoffrey M. Garner and Kees den Hollander, *Analysis of Clock Synchronization Approaches for Residential Ethernet*, Samsung presentation to September, 2005 IEEE 802.3 ResE SG Meeting, San Jose, CA, USA, September 29, 2005. Available at http://www.ieee802.org/3/re_study/public/200509/garner_1.pdf.
2. Geoffrey M. Garner, *Additional Simulation Results for ResE Synchronization Using Filtered Phase and Instantaneous Frequency Adjustments*, Samsung presentation to November, 2005 IEEE 802.3 ResE SG Meeting, Vancouver, BC, Canada, November 14, 2005. Available at http://www.ieee802.org/3/re_study/public/200511/20051114-garner-synch-simul.pdf.
3. Geoffrey M. Garner, *Initial Simulation Results for AVB Synchronization Transported using IEEE 1588 Peer-to-Peer Transparent Clocks*, Samsung presentation to May, 2006 IEEE 802.1 AVB TG Meeting, Beijing, China, May 16, 2006. Available at http://www.ieee802.org/1/files/public/docs2006/as-gmg-simul-resul-p2p-tc-transport-060516.pdf.
4. Geoffrey M. Garner, *Further Simulation Results for AVB Synchronization Transported using IEEE 1588 Peer-to-Peer Transparent Clocks*, Samsung presentation to July, 2006 IEEE 802.1 AVB TG Meeting, San Diego, CA, USA, July 12, 2006. Available at http://www.ieee802.org/1/files/public/docs2006/as-gmg-further-simul-resul-p2p-tc-transport-060712.pdf

References – 2

4. Don Pannell and Michael Johas Teener, *Audio/Video Bridging (AVB) Assumptions*, July, 2008 – Denver, CO (annotated Sept 2008 – Seoul, Korea) (available at http://www.ieee802.org/1/files/public/docs2008/avb-pannell-mjt-assumptions-0908-v17.pdf).
5. Geoffrey M. Garner, *Improvement of Jitter, Wander, and Time Synchronization Performance in 802.1AS Wired Transport using Propagation Time Averaging*, Samsung presentation to January, 2007 IEEE 802.1 AVB TG Meeting, Monterey, CA, USA, January 24, 2007. Available at http://www.ieee802.org/1/files/public/docs2007/as-garner-prop-time-averaging-0107.pdf
6. Geoffrey M. Garner, Initial Comparison of 802.1AS Jitter/Wander Performance with and without Propagation Time Averaging, Samsung presentation to May, 2009 IEEE 802.1 AVB TG Meeting, Pittsburgh, PA, USA, May 11, 2009.

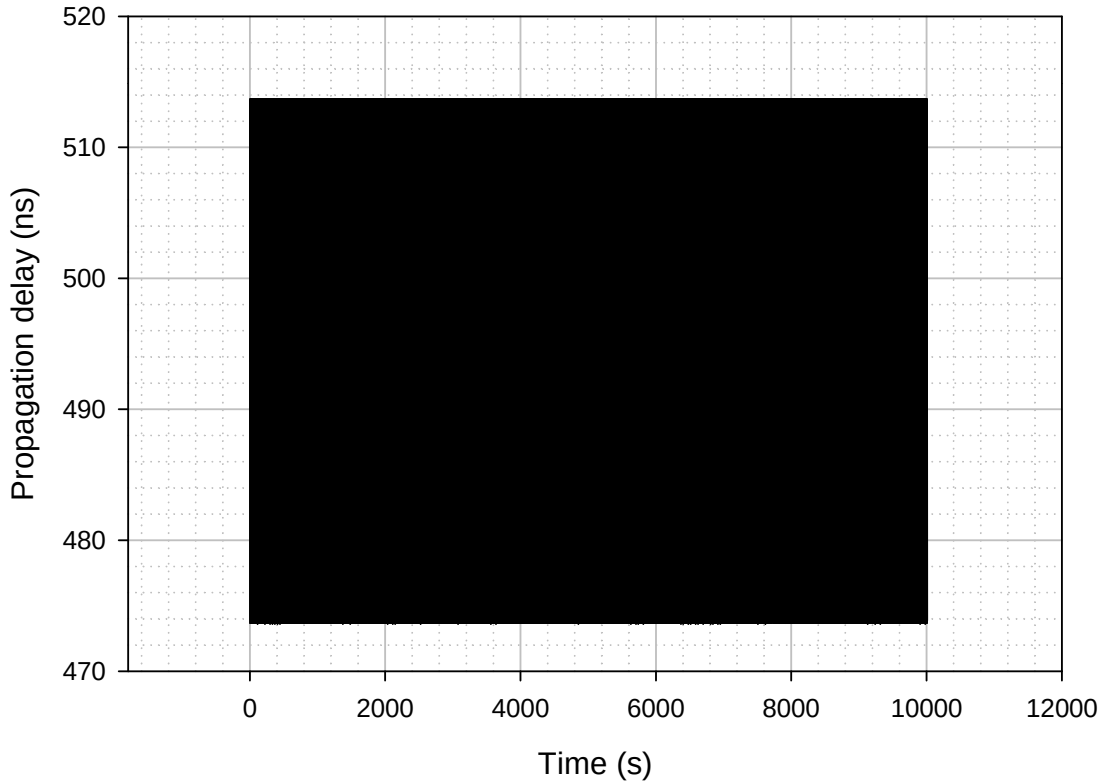
References – 3

7. Geoffrey M. Garner, *End-to-End Jitter and Wander Requirements for ResE Applications*, Samsung presentation to May, 2005 IEEE 802.3 ResE SG Meeting, Austin, TX, USA, May 12, 2005. Available at http://www.ieee802.org/3/re_study/public/200505/garner_3_0505.pdf
8. Kees den Hollander and Geoffrey M. Garner, *IEEE 802.1AS Timing and Synchronization and Its Applications*, 4th International Telecoms Synchronization Forum, ITSF 2006.
9. J. Kevin Rhee, Kyusang Lee, and Seung-Hwan Kim, *Synchronization Requirements in Cellular Networks over Ethernet*, presentation by Kaist, Actus Networks, and ETRI to IEEE 802.1 Time Synchronization Study Group, Quebec City, Quebec, Canada, May, 2009.

BACKUP

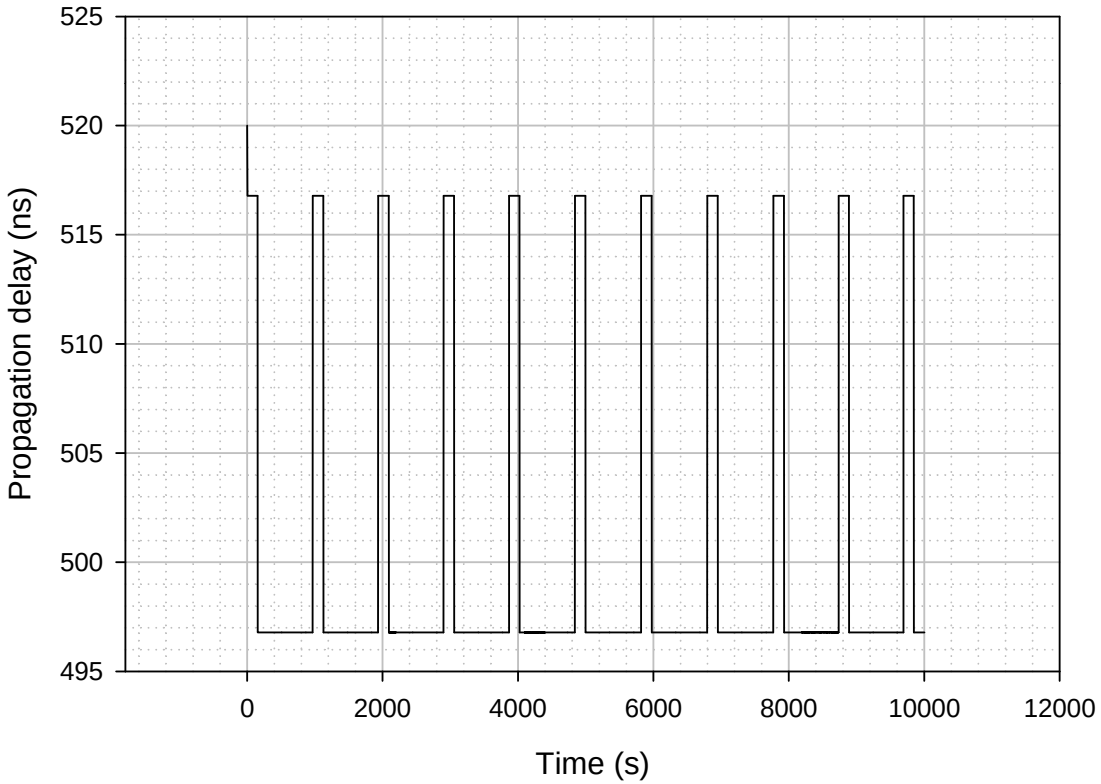
Case 1-01, Node 7 to 8 Propagation Delay

Case 1-01,Node 7 to 8 propagation delay
(after initialization)
Sync Interval = 0.01 s
Pdelay Interval = 0.1 s
Endpoint filter BW = 0.01 Hz
Local oscillator tolerance = +/- 100 ppm
(frequency offsets initialized randomly within tolerance range)



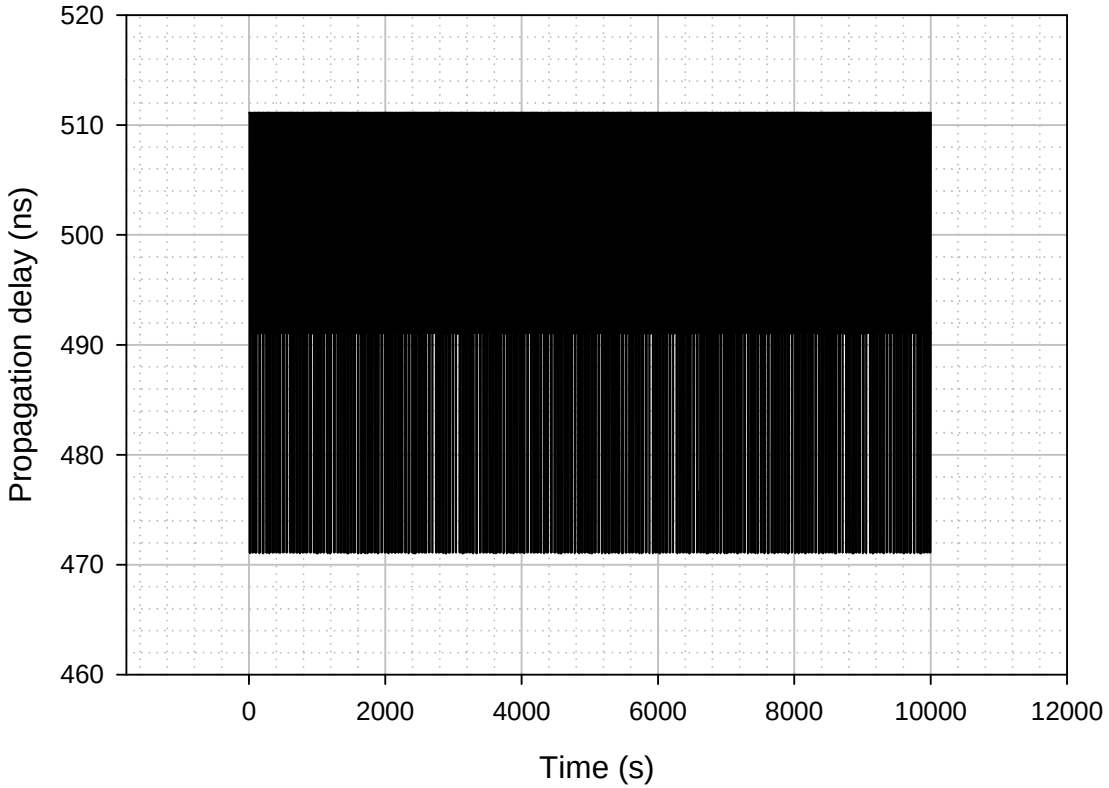
Case 1-125, Node 1 to 2 Propagation Delay

Case 1-125,Node 1 to 2 propagation delay
(after initialization)
Sync Interval = 0.125 s
Pdelay Interval = 1.0 s
Endpoint filter BW = 0.01 Hz
Local oscillator tolerance = +/- 100 ppm
(frequency offsets initialized randomly within tolerance range)



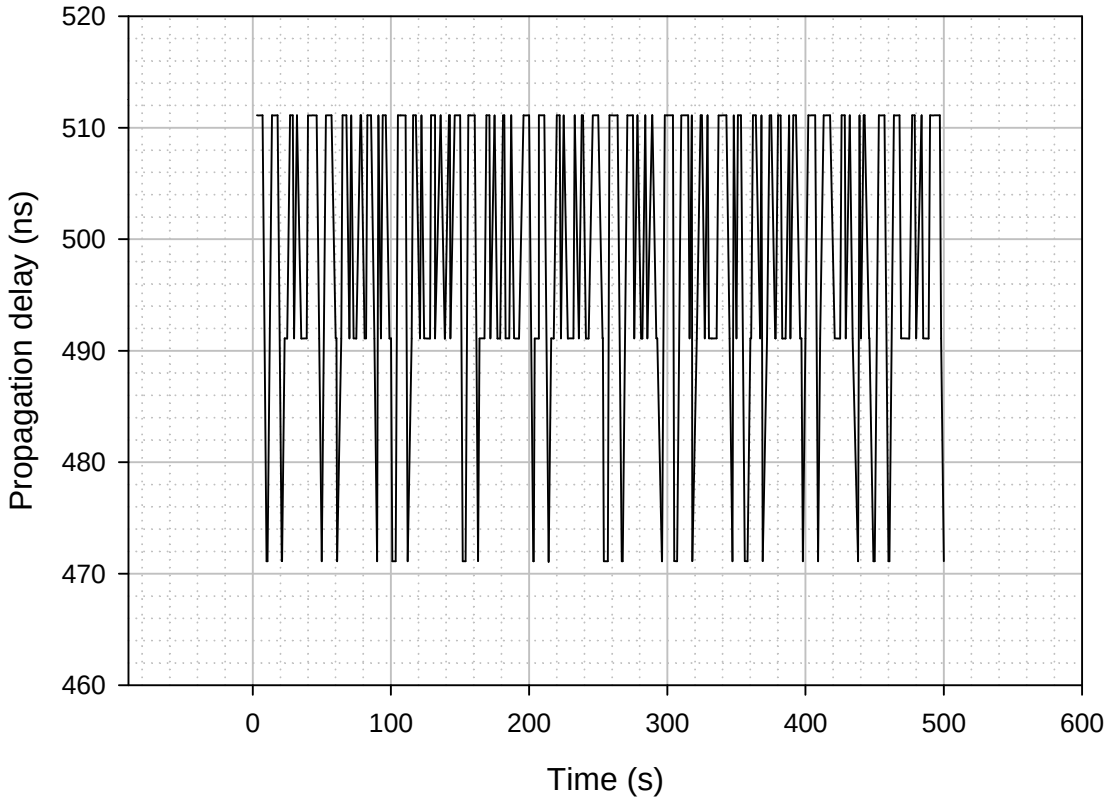
Case 1-125, Node 2 to 3 Propagation Delay

Case 1-125,Node 2 to 3 propagation delay
(after initialization)
Sync Interval = 0.125 s
Pdelay Interval = 1.0 s
Endpoint filter BW = 0.01 Hz
Local oscillator tolerance = +/- 100 ppm
(frequency offsets initialized randomly within tolerance range)



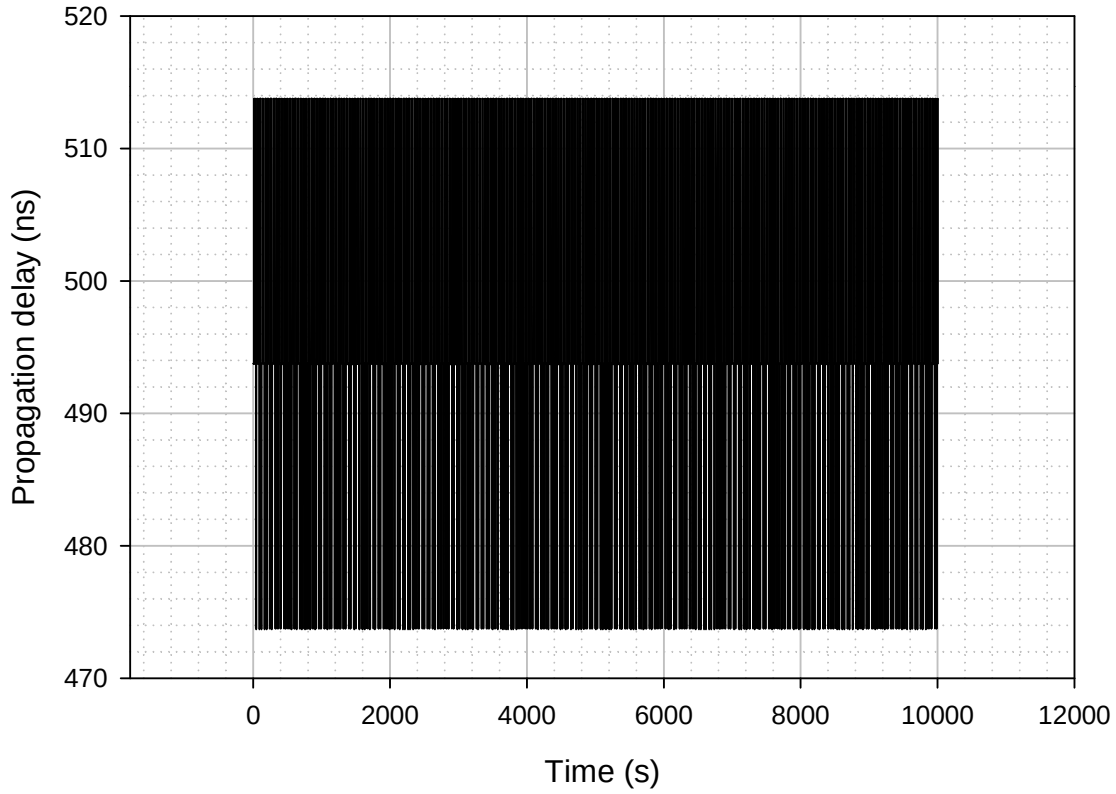
Case 1-125, Node 2 to 3 Propagation Delay, Detail of First 500 s

Case 1-125,Node 2 to 3 propagation delay
(after initialization)
detail of first 500 s
Sync Interval = 0.125 s
Pdelay Interval = 1.0 s
Endpoint filter BW = 0.01 Hz
Local oscillator tolerance = +/- 100 ppm
(frequency offsets initialized randomly within tolerance range)



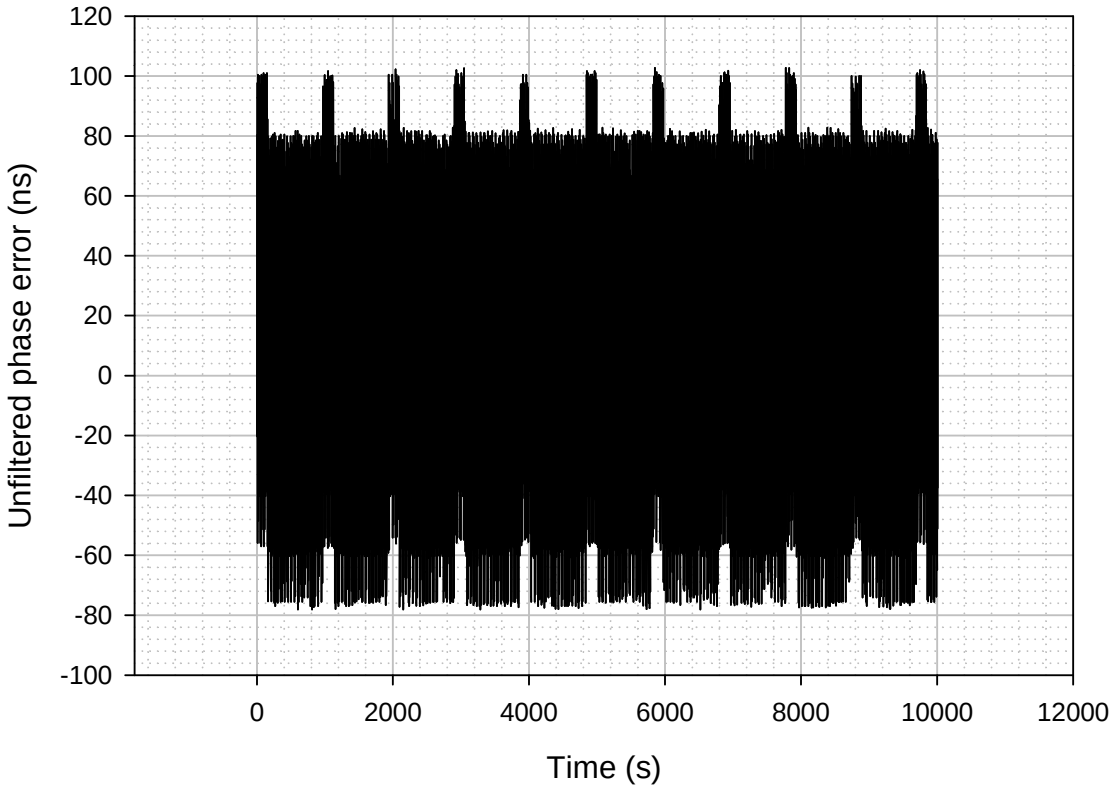
Case 1-125, Node 7 to 8 Propagation Delay

Case 1-125,Node 7 to 8 propagation delay
(after initialization)
Sync Interval = 0.125 s
Pdelay Interval = 1.0 s
Endpoint filter BW = 0.01 Hz
Local oscillator tolerance = +/- 100 ppm
(frequency offsets initialized randomly within tolerance range)



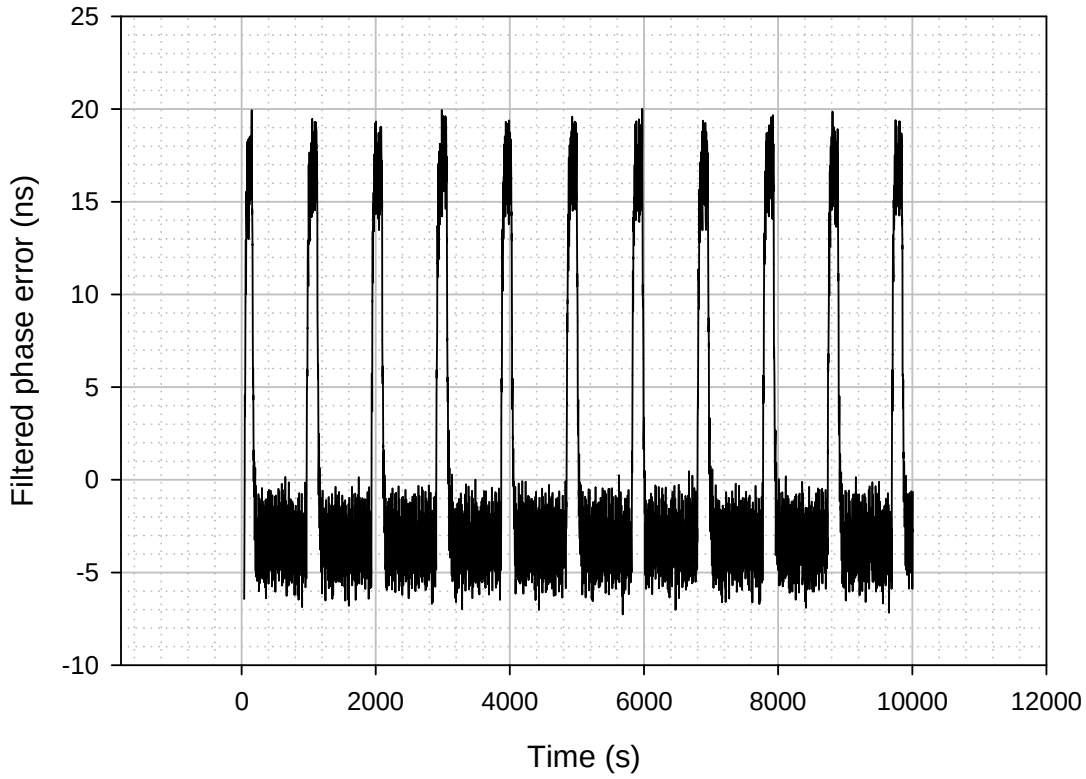
Case 1-125, Node 3 – Unfiltered Phase Error, after initial transient

Case 1-125,Node 3
Unfiltered phase error, initial transient removed
Sync Interval = 0.125 s
Pdelay Interval = 1.0 s
Endpoint filter BW = 0.01 Hz
Local oscillator tolerance = +/- 100 ppm
(frequency offsets initialized randomly within tolerance range)



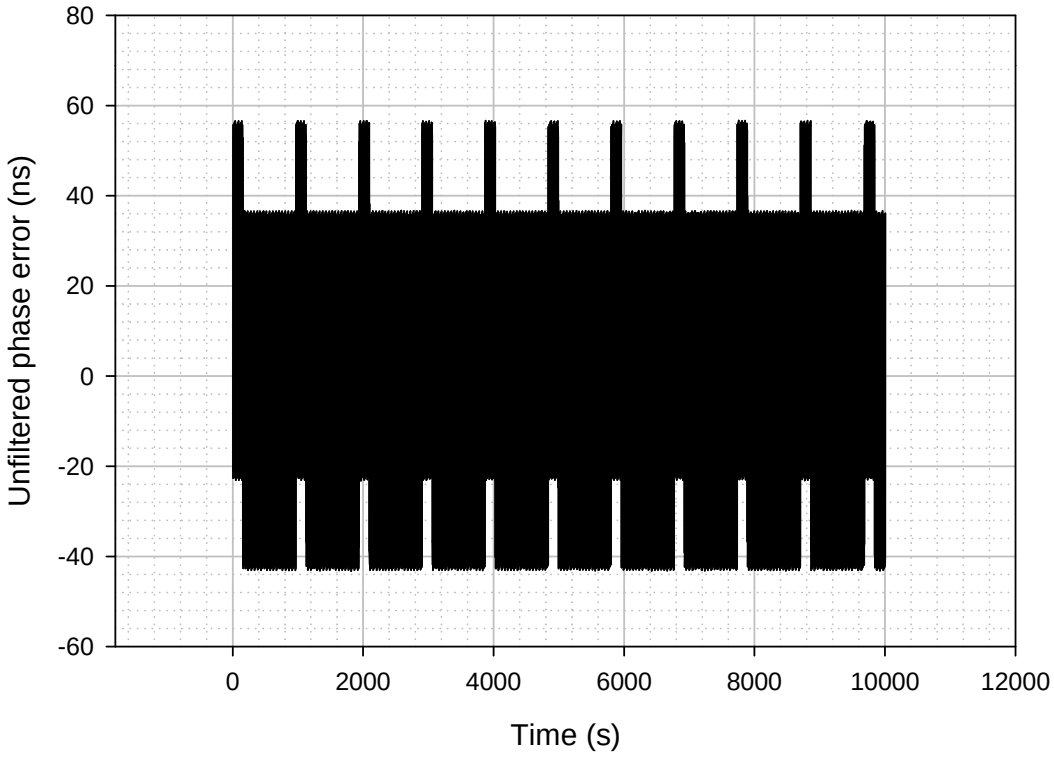
Case 1-125, Node 3 – Filtered Phase Error

Case 1-125,Node 3
Filtered phase error (initial transient removed)
Sync Interval = 0.125 s
Pdelay Interval = 1.0 s
Endpoint filter BW = 0.01 Hz
Local oscillator tolerance = +/- 100 ppm
(frequency offsets initialized randomly within tolerance range)



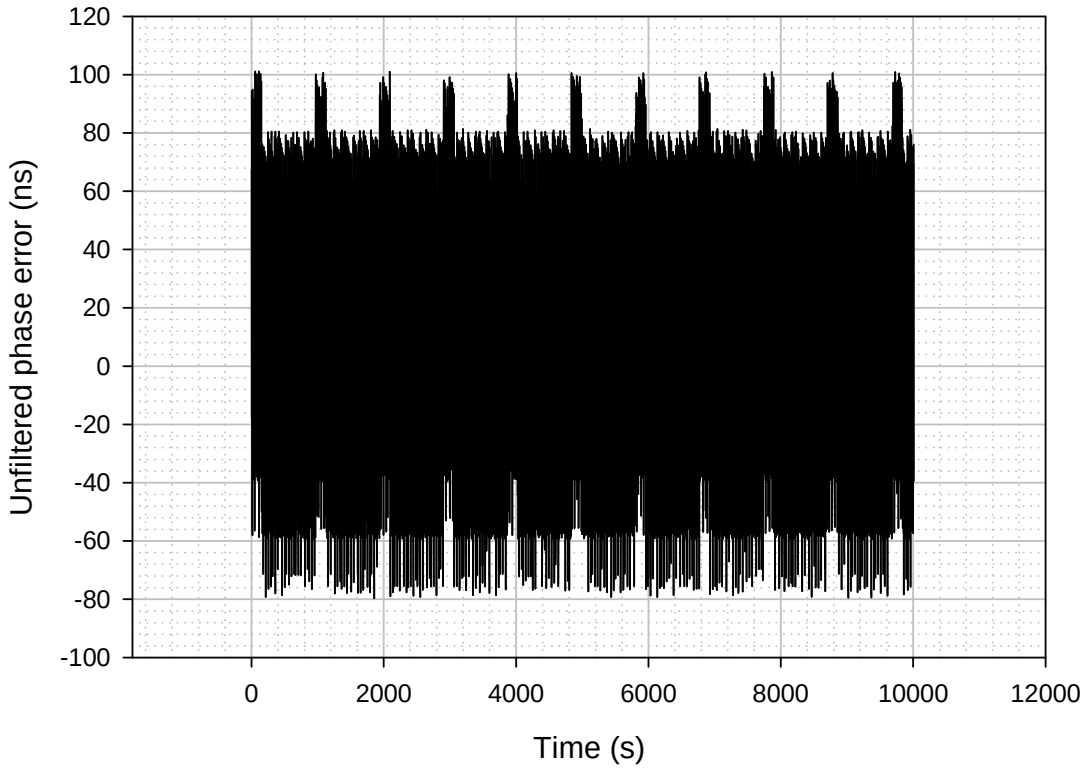
Case 1-250, Node 2 – Unfiltered Phase Error, after initial transient

Case 1-250,Node 2
Unfiltered phase error, initial transient removed
Sync Interval = 0.250 s
Pdelay Interval = 2.0 s
Endpoint filter BW = 0.01 Hz
Local oscillator tolerance = +/- 100 ppm
(frequency offsets initialized randomly within tolerance range)



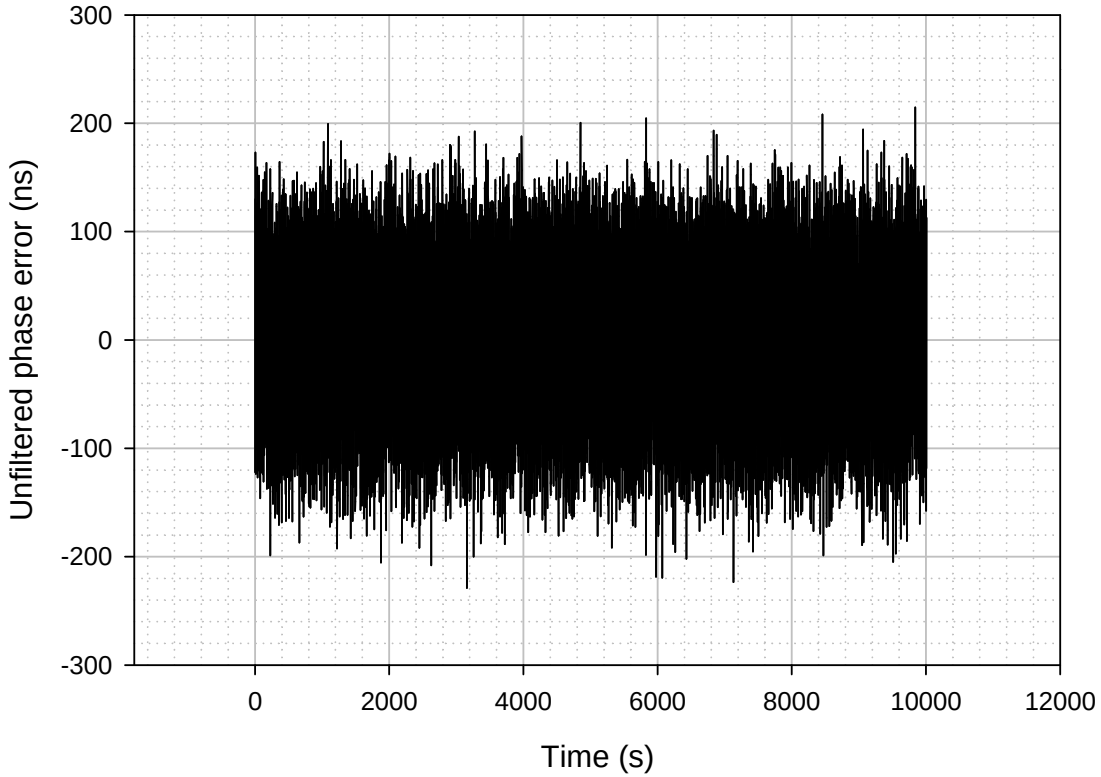
Case 1-250, Node 3 – Unfiltered Phase Error, after initial transient

Case 1-250,Node 3
Unfiltered phase error, initial transient removed
Sync Interval = 0.250 s
Pdelay Interval = 2.0 s
Endpoint filter BW = 0.01 Hz
Local oscillator tolerance = +/- 100 ppm
(frequency offsets initialized randomly within tolerance range)



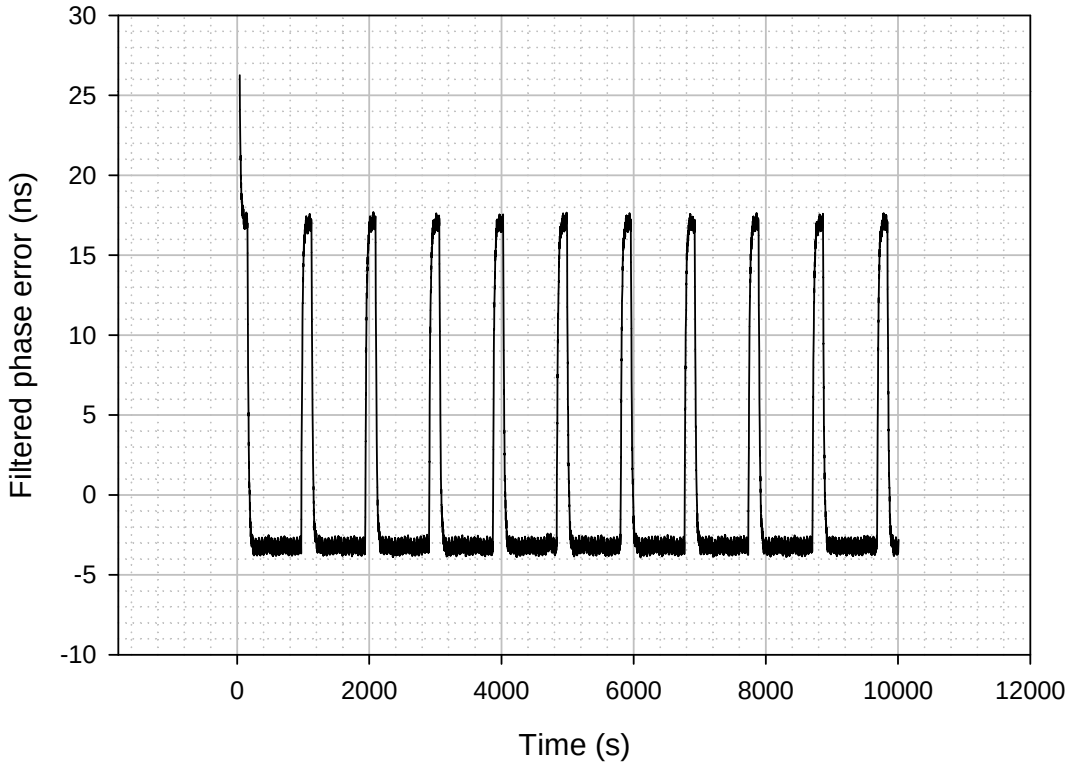
Case 1-250, Node 8 – Unfiltered Phase Error, after initial transient

Case 1-250,Node 8
Unfiltered phase error, initial transient removed
Sync Interval = 0.250 s
Pdelay Interval = 2.0 s
Endpoint filter BW = 0.01 Hz
Local oscillator tolerance = +/- 100 ppm
(frequency offsets initialized randomly within tolerance range)



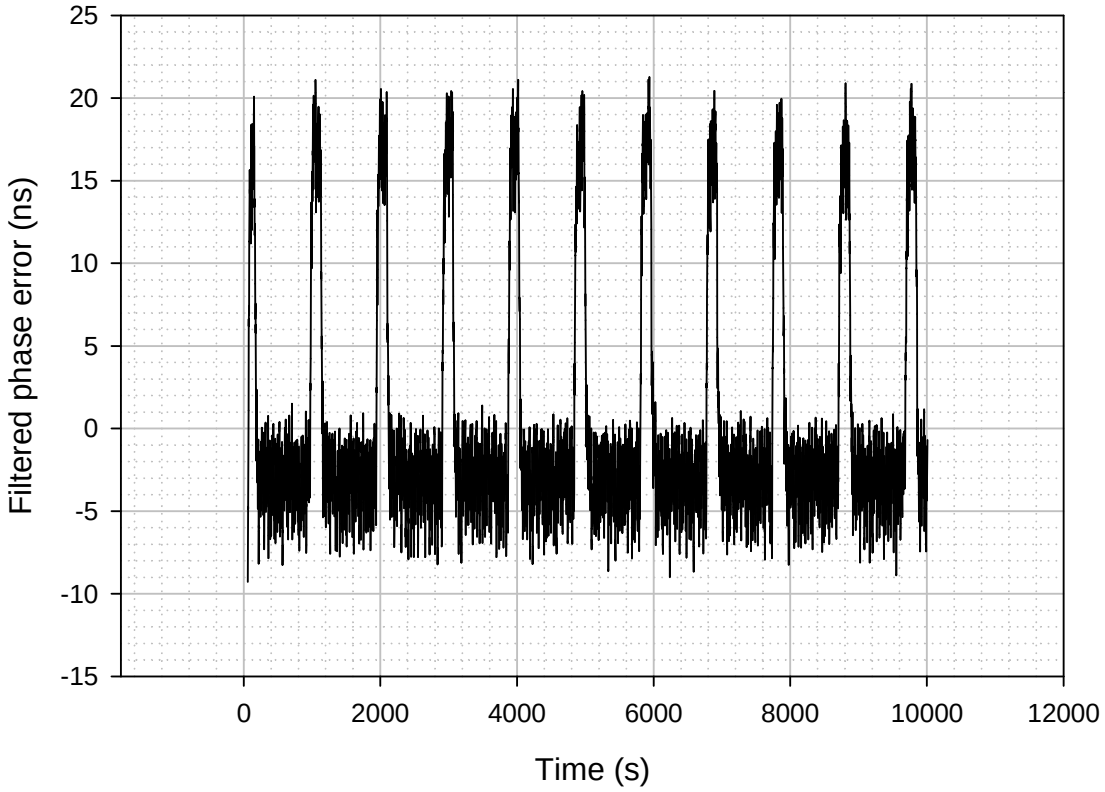
Case 1-250, Node 2 – Filtered Phase Error

Case 1-250,Node 2
Filtered phase error, initial transient removed
Sync Interval = 0.250 s
Pdelay Interval = 2.0 s
Endpoint filter BW = 0.01 Hz
Local oscillator tolerance = +/- 100 ppm
(frequency offsets initialized randomly within tolerance range)



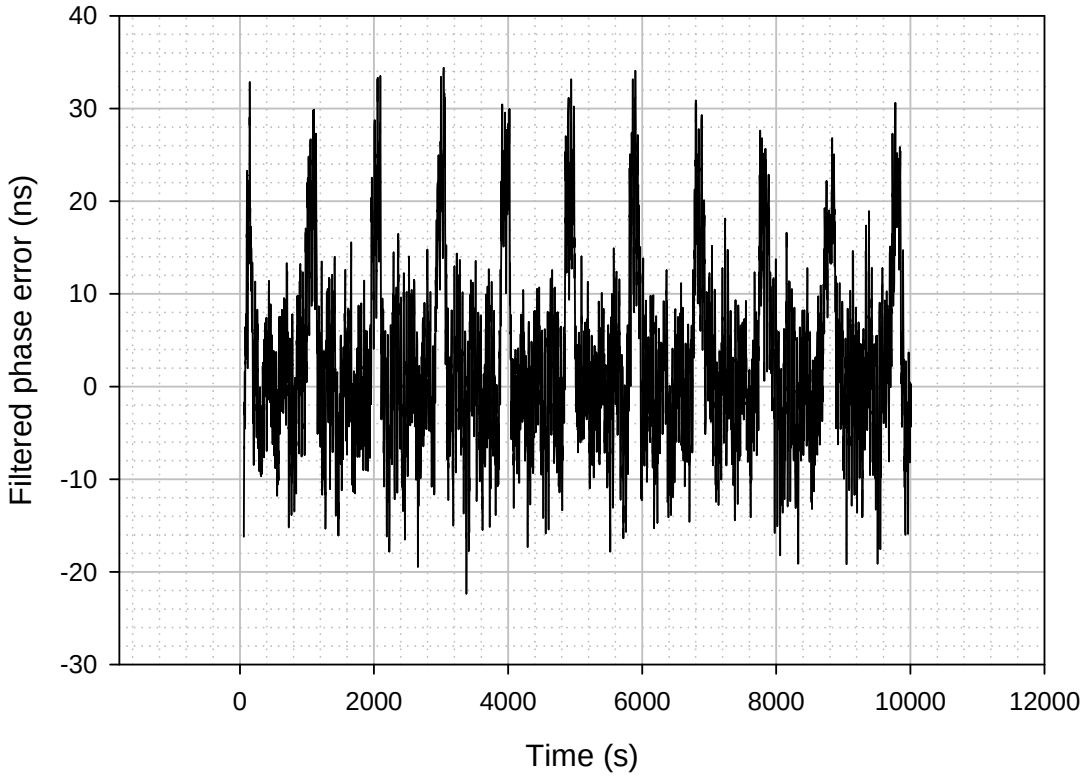
Case 1-250, Node 3 – Filtered Phase Error

Case 1-250,Node 3
Filtered phase error, initial transient removed
Sync Interval = 0.250 s
Pdelay Interval = 2.0 s
Endpoint filter BW = 0.01 Hz
Local oscillator tolerance = +/- 100 ppm
(frequency offsets initialized randomly within tolerance range)



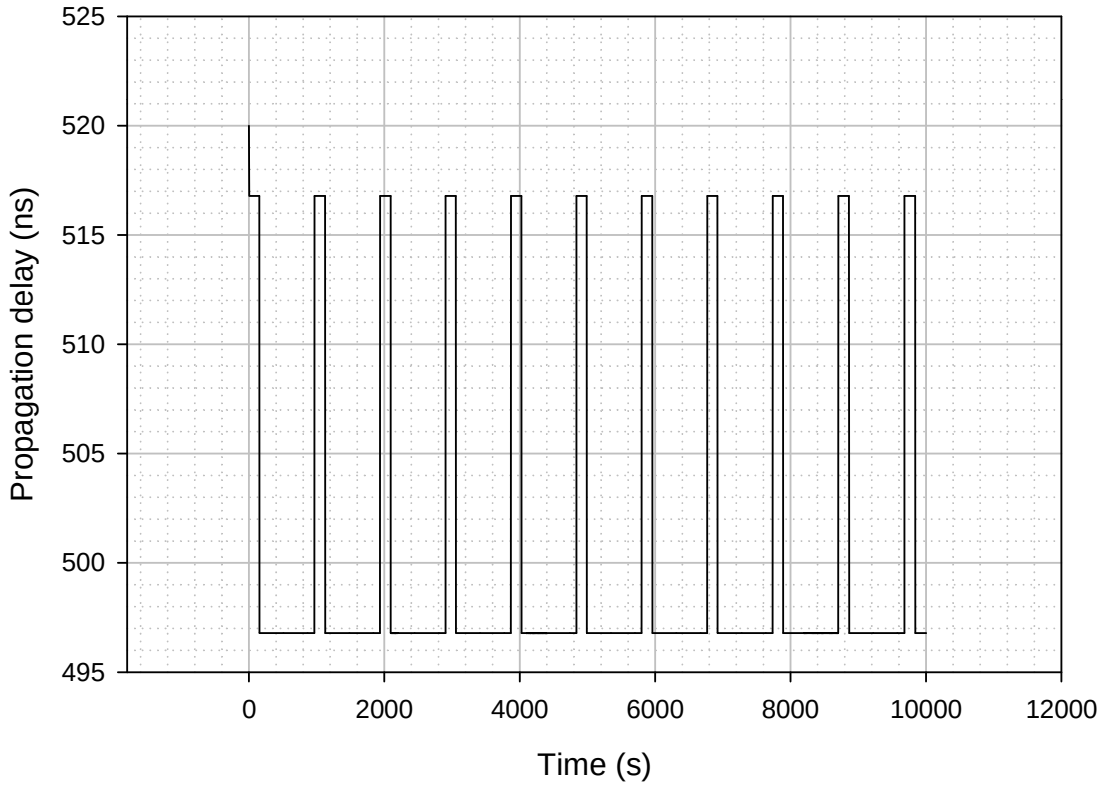
Case 1-250, Node 8 – Filtered Phase Error

Case 1-250,Node 8
Filtered phase error, initial transient removed
Sync Interval = 0.250 s
Pdelay Interval = 2.0 s
Endpoint filter BW = 0.01 Hz
Local oscillator tolerance = +/- 100 ppm
(frequency offsets initialized randomly within tolerance range)



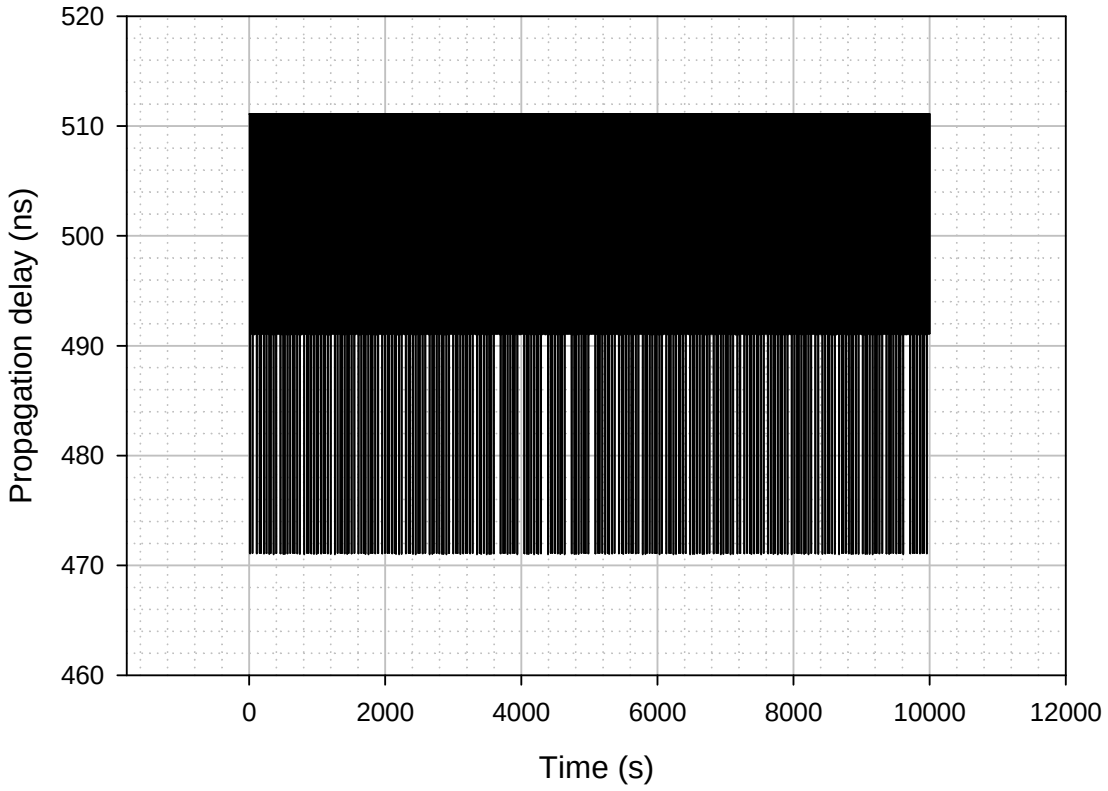
Case 1-250, Node 1 to 2 Propagation Delay

Case 1-250,Node 1 to 2 propagation delay
(after initialization)
Sync Interval = 0.250 s
Pdelay Interval = 2.0 s
Endpoint filter BW = 0.01 Hz
Local oscillator tolerance = +/- 100 ppm
(frequency offsets initialized randomly within tolerance range)



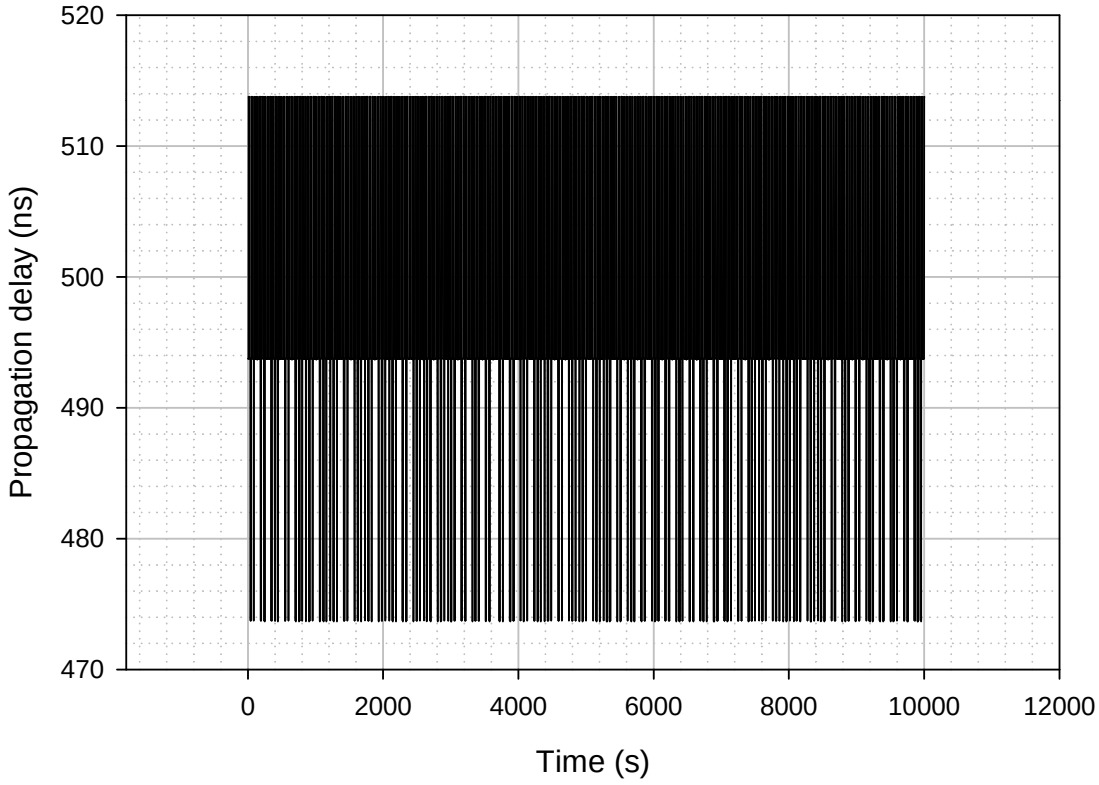
Case 1-250, Node 2 to 3 Propagation Delay

Case 1-250,Node 2 to 3 propagation delay
(after initialization)
Sync Interval = 0.250 s
Pdelay Interval = 2.0 s
Endpoint filter BW = 0.01 Hz
Local oscillator tolerance = +/- 100 ppm
(frequency offsets initialized randomly within tolerance range)



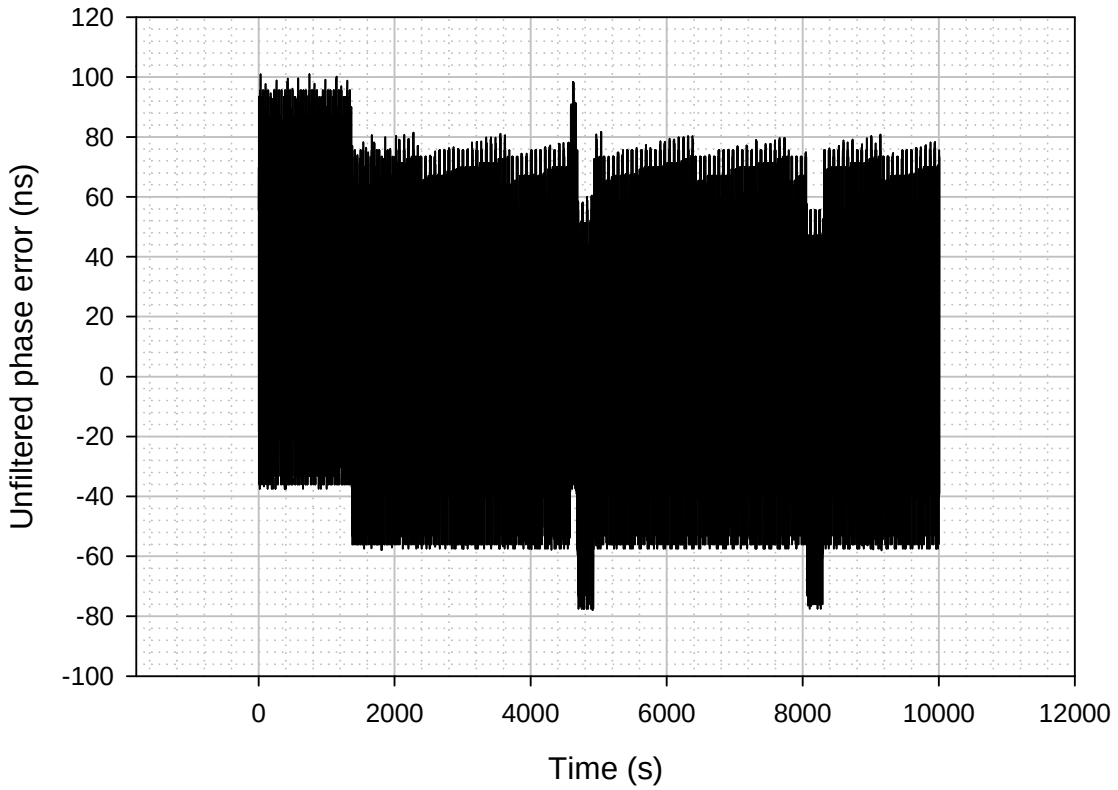
Case 1-250, Node 7 to 8 Propagation Delay

Case 1-250,Node 7 to 8 propagation delay
(after initialization)
Sync Interval = 0.250 s
Pdelay Interval = 2.0 s
Endpoint filter BW = 0.01 Hz
Local oscillator tolerance = +/- 100 ppm
(frequency offsets initialized randomly within tolerance range)



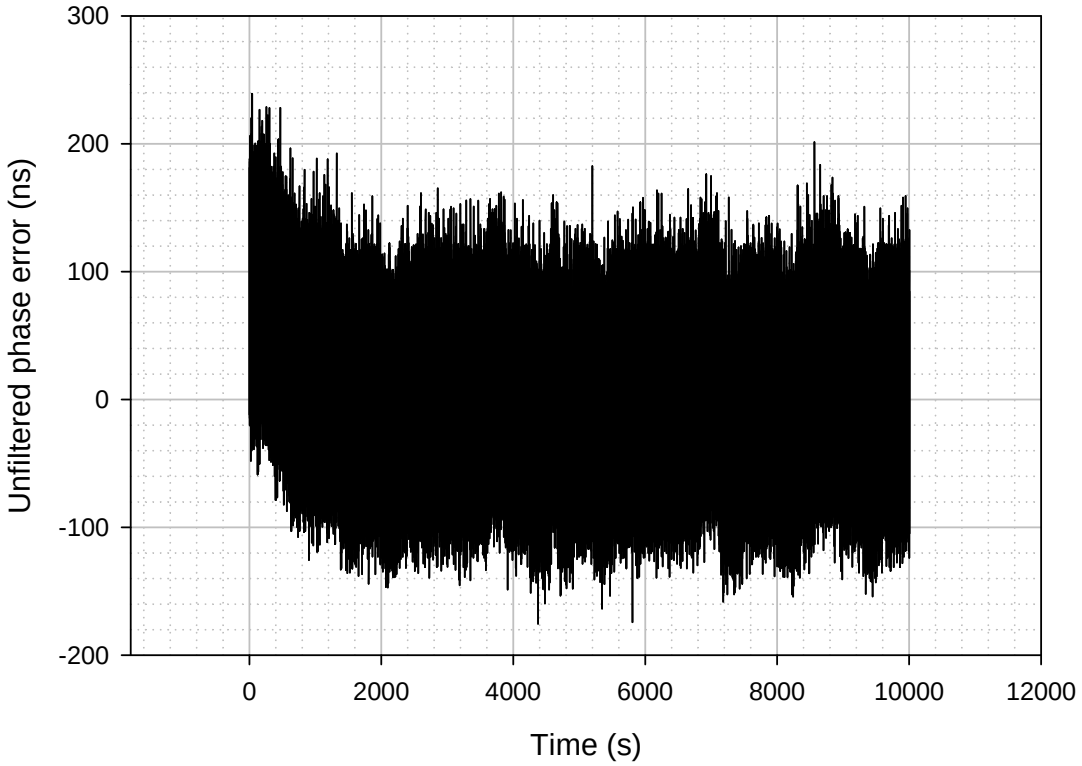
Case 2-01, Node 3 – Unfiltered Phase Error, after initial transient

Case 2-01,Node 3
Unfiltered phase error, initial transient removed
Sync Interval = 0.01 s
Pdelay Interval = 0.1 s
Endpoint filter BW = 0.01 Hz
Local oscillator tolerance = +/- 5 ppm
(frequency offsets initialized randomly within tolerance range)



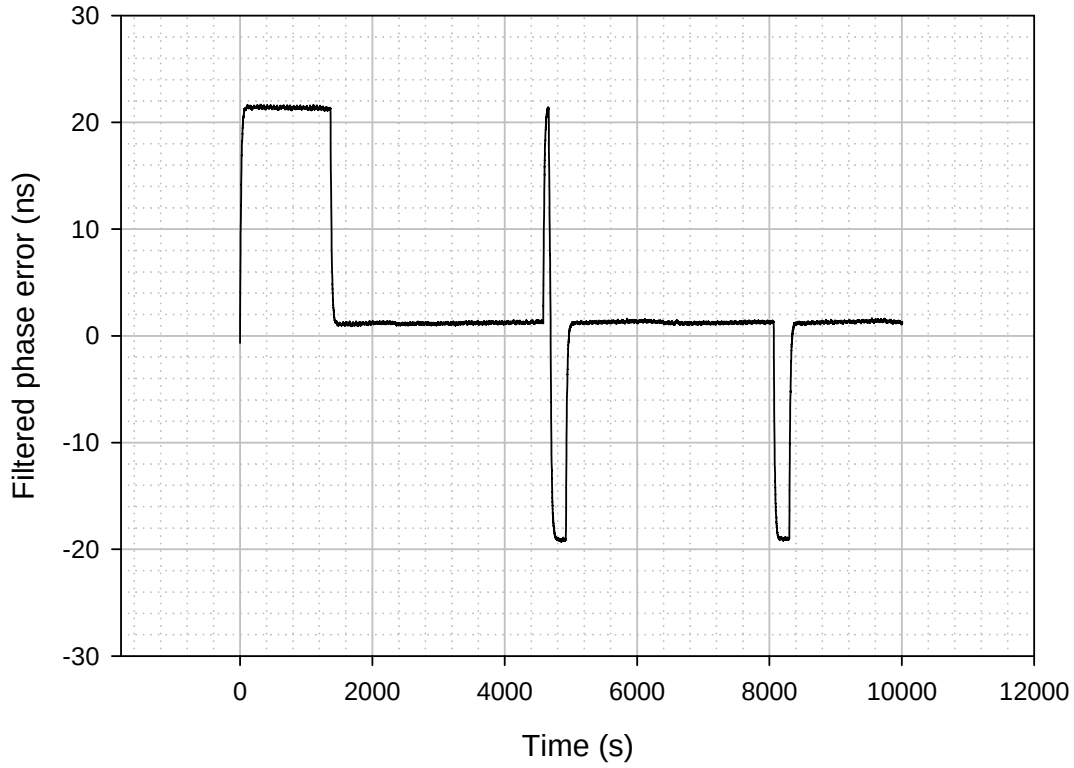
Case 2-01, Node 8 – Unfiltered Phase Error, after initial transient

Case 2-01,Node 8
Unfiltered phase error, initial transient removed
Sync Interval = 0.01 s
Pdelay Interval = 0.1 s
Endpoint filter BW = 0.01 Hz
Local oscillator tolerance = +/- 5 ppm
(frequency offsets initialized randomly within tolerance range)



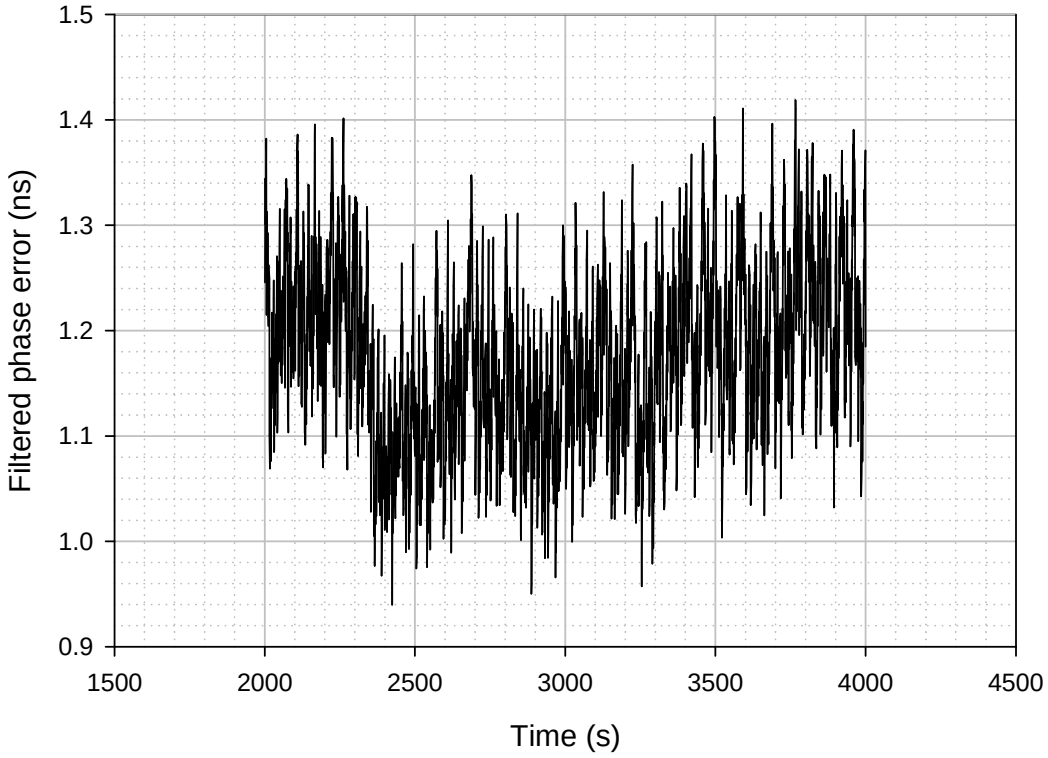
Case 2-01, Node 3 – Filtered Phase Error

Case 2-01,Node 3
Filtered phase error
Sync Interval = 0.01 s
Pdelay Interval = 0.1 s
Endpoint filter BW = 0.01 Hz
Local oscillator tolerance = +/- 5 ppm
(frequency offsets initialized randomly within tolerance range)



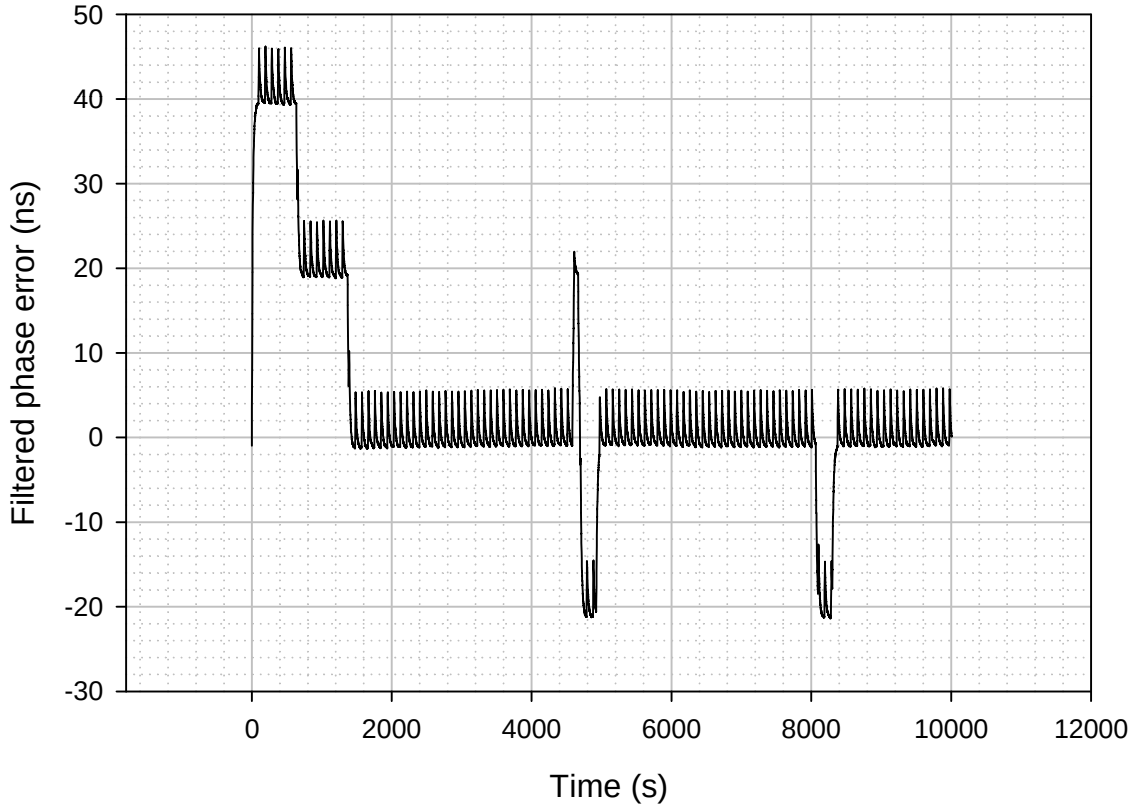
Case 2-01, Node 3 – Filtered Phase Error, Detail of 2000 – 4000 s

Case 2-01,Node 3
Filtered phase error, detail of 2000 - 4000 s
Sync Interval = 0.01 s
Pdelay Interval = 0.1 s
Endpoint filter BW = 0.01 Hz
Local oscillator tolerance = +/- 5 ppm
(frequency offsets initialized randomly within tolerance range)



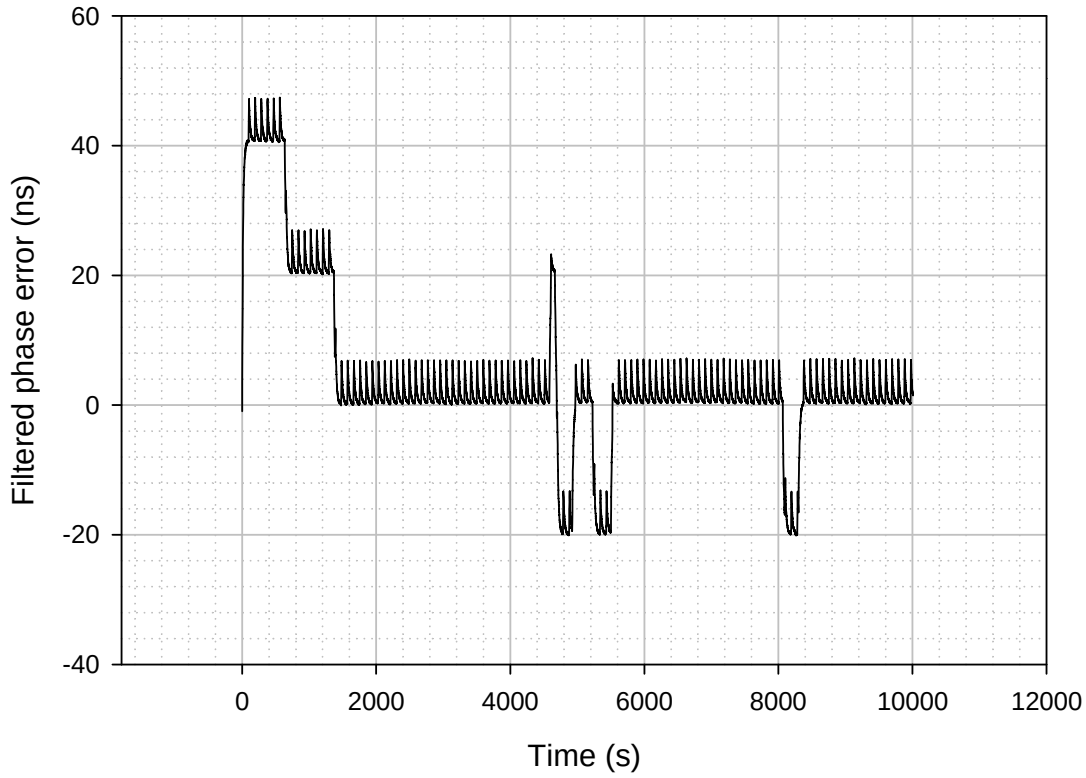
Case 2-01, Node 4 – Filtered Phase Error

Case 2-01,Node 4
Filtered phase error
Sync Interval = 0.01 s
Pdelay Interval = 0.1 s
Endpoint filter BW = 0.01 Hz
Local oscillator tolerance = +/- 5 ppm
(frequency offsets initialized randomly within tolerance range)



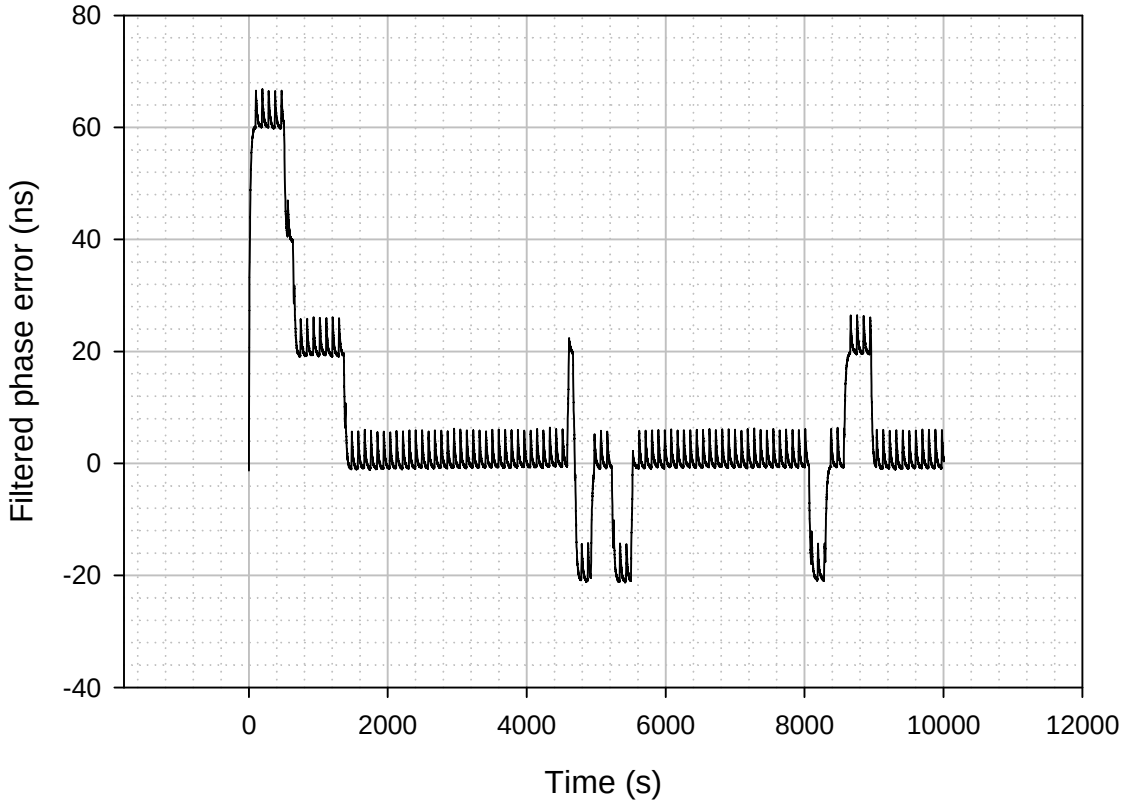
Case 2-01, Node 5 – Filtered Phase Error

Case 2-01,Node 5
Filtered phase error
Sync Interval = 0.01 s
Pdelay Interval = 0.1 s
Endpoint filter BW = 0.01 Hz
Local oscillator tolerance = +/- 5 ppm
(frequency offsets initialized randomly within tolerance range)



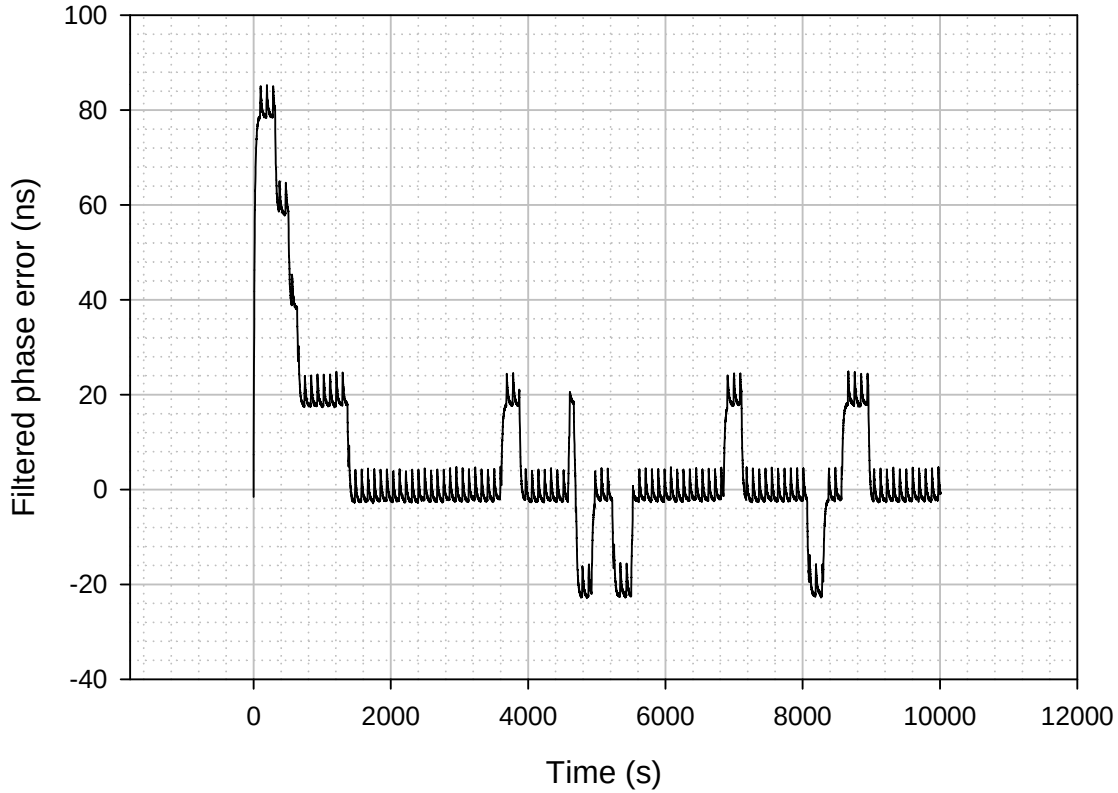
Case 2-01, Node 6 – Filtered Phase Error

Case 2-01,Node 6
Filtered phase error
Sync Interval = 0.01 s
Pdelay Interval = 0.1 s
Endpoint filter BW = 0.01 Hz
Local oscillator tolerance = +/- 5 ppm
(frequency offsets initialized randomly within tolerance range)



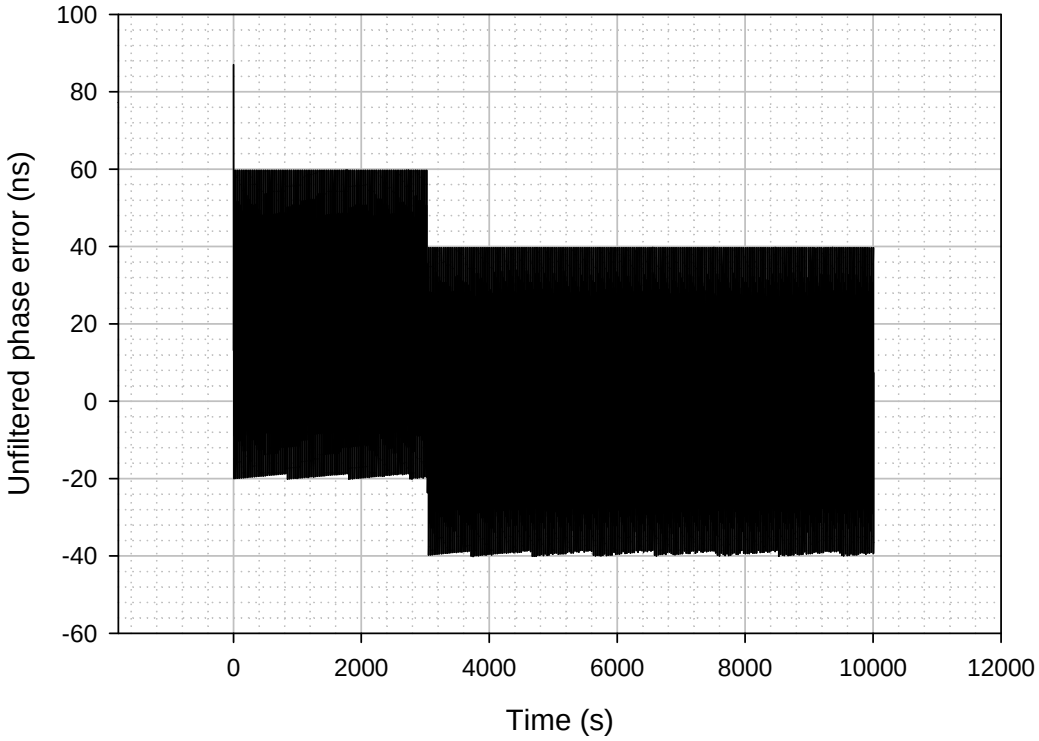
Case 2-01, Node 7 – Filtered Phase Error

Case 2-01,Node 7
Filtered phase error
Sync Interval = 0.01 s
Pdelay Interval = 0.1 s
Endpoint filter BW = 0.01 Hz
Local oscillator tolerance = +/- 5 ppm
(frequency offsets initialized randomly within tolerance range)



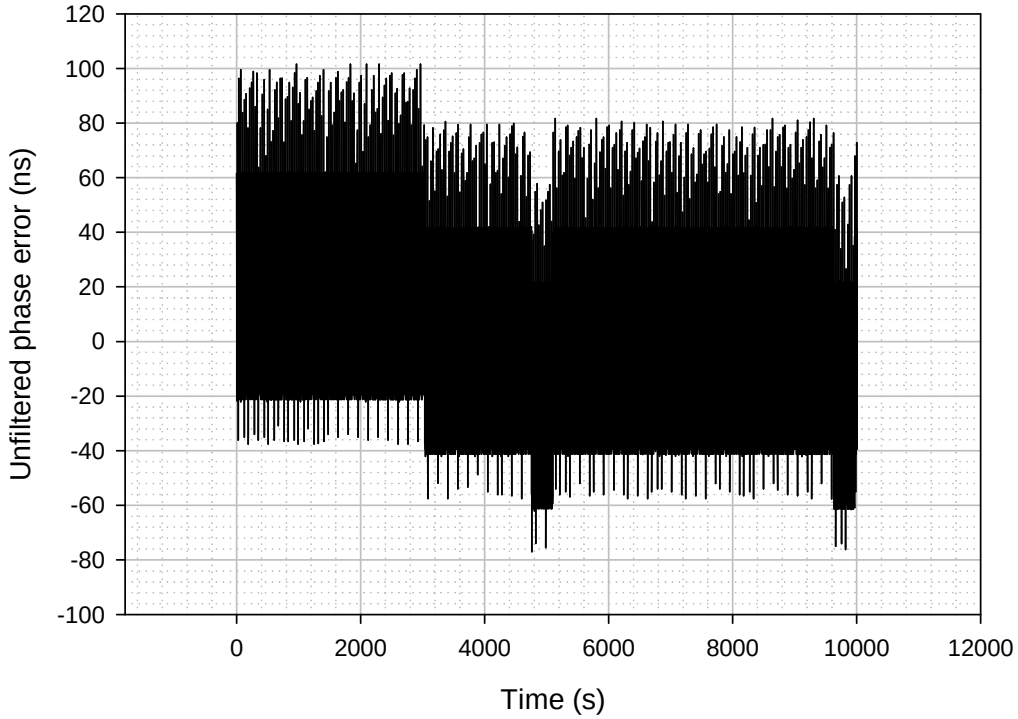
Case 2-125, Node 2 – Unfiltered Phase Error after initial transient

Case 2-125,Node 2
Unfiltered phase error, initial transient removed
Sync Interval = 0.125 s
Pdelay Interval = 1.0 s
Endpoint filter BW = 0.01 Hz
Local oscillator tolerance = +/- 5 ppm
(frequency offsets initialized randomly within tolerance range)



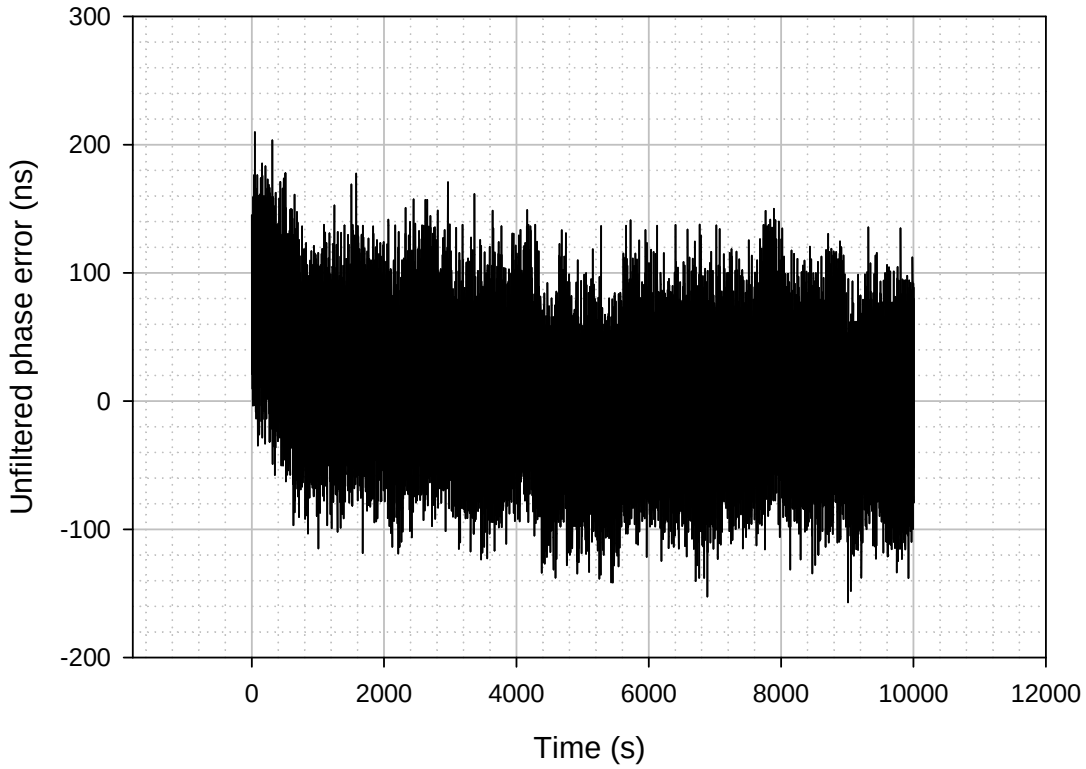
Case 2-125, Node 3 – Unfiltered Phase Error, after initial transient

Case 2-125,Node 3
Unfiltered phase error, initial transient removed
Sync Interval = 0.125 s
Pdelay Interval = 1.0 s
Endpoint filter BW = 0.01 Hz
Local oscillator tolerance = +/- 5 ppm
(frequency offsets initialized randomly within tolerance range)



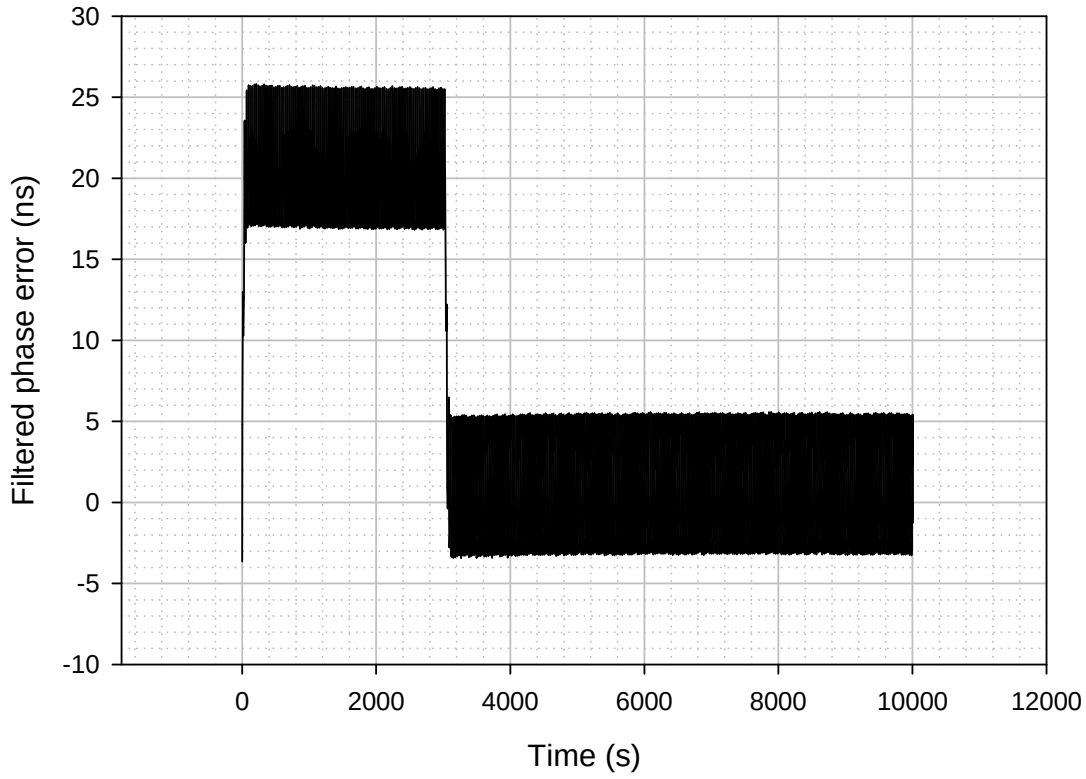
Case 2-125, Node 8 – Unfiltered Phase Error, after initial transient

Case 2-125,Node 8
Unfiltered phase error, initial transient removed
Sync Interval = 0.125 s
Pdelay Interval = 1.0 s
Endpoint filter BW = 0.01 Hz
Local oscillator tolerance = +/- 5 ppm
(frequency offsets initialized randomly within tolerance range)



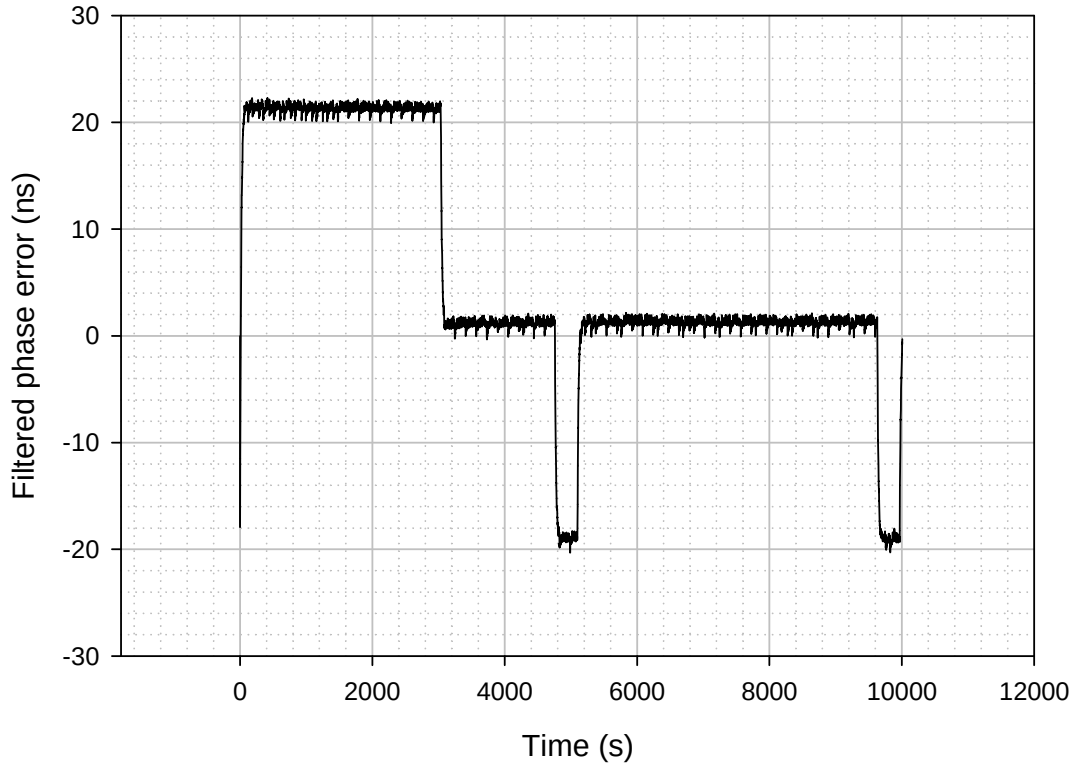
Case 2-125, Node 2 – Filtered Phase Error

Case 2-125,Node 2
Filtered phase error
Sync Interval = 0.125 s
Pdelay Interval = 1.0 s
Endpoint filter BW = 0.01 Hz
Local oscillator tolerance = +/- 5 ppm
(frequency offsets initialized randomly within tolerance range)



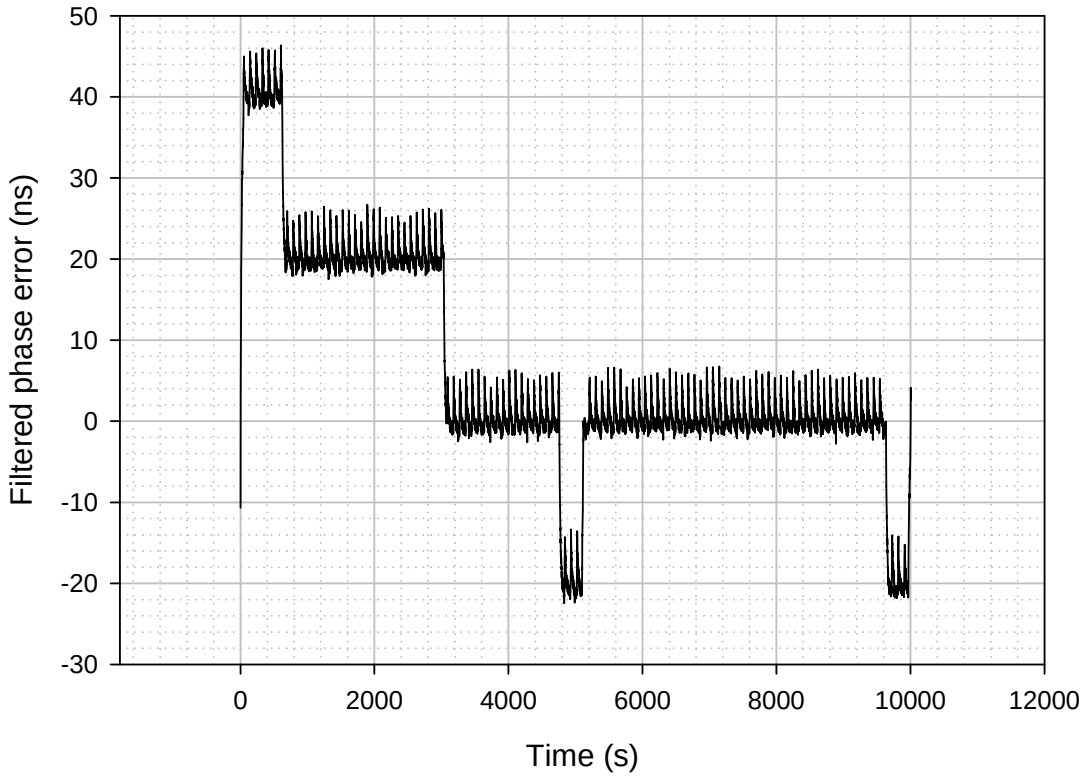
Case 2-125, Node 3 – Filtered Phase Error

Case 2-125,Node 3
Filtered phase error
Sync Interval = 0.125 s
Pdelay Interval = 1.0 s
Endpoint filter BW = 0.01 Hz
Local oscillator tolerance = +/- 5 ppm
(frequency offsets initialized randomly within tolerance range)



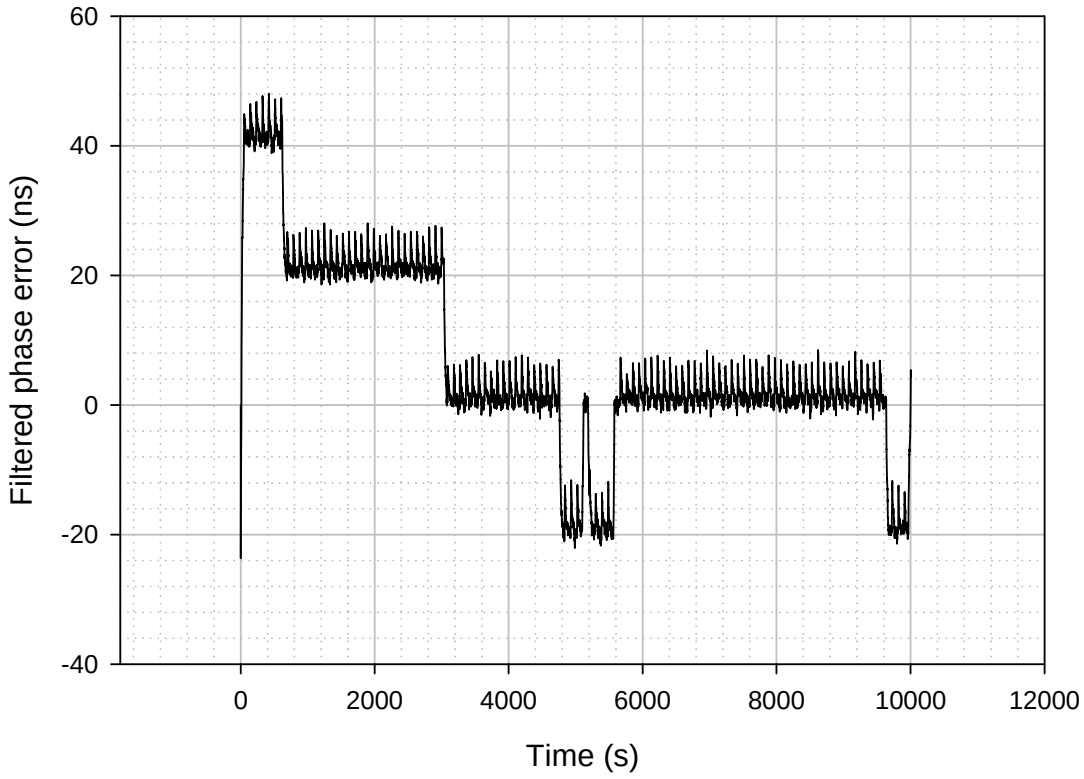
Case 2-125, Node 4 – Filtered Phase Error

Case 2-125,Node 4
Filtered phase error
Sync Interval = 0.125 s
Pdelay Interval = 1.0 s
Endpoint filter BW = 0.01 Hz
Local oscillator tolerance = +/- 5 ppm
(frequency offsets initialized randomly within tolerance range)



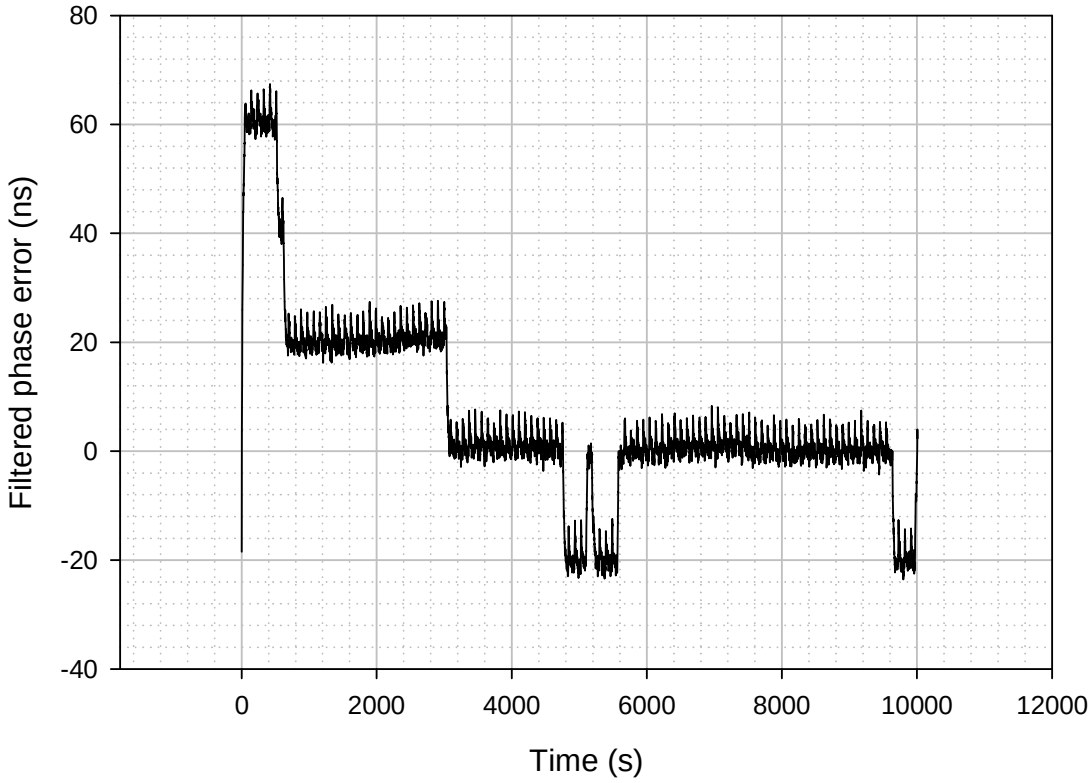
Case 2-125, Node 5 – Filtered Phase Error

Case 2-125,Node 5
Filtered phase error
Sync Interval = 0.125 s
Pdelay Interval = 1.0 s
Endpoint filter BW = 0.01 Hz
Local oscillator tolerance = +/- 5 ppm
(frequency offsets initialized randomly within tolerance range)



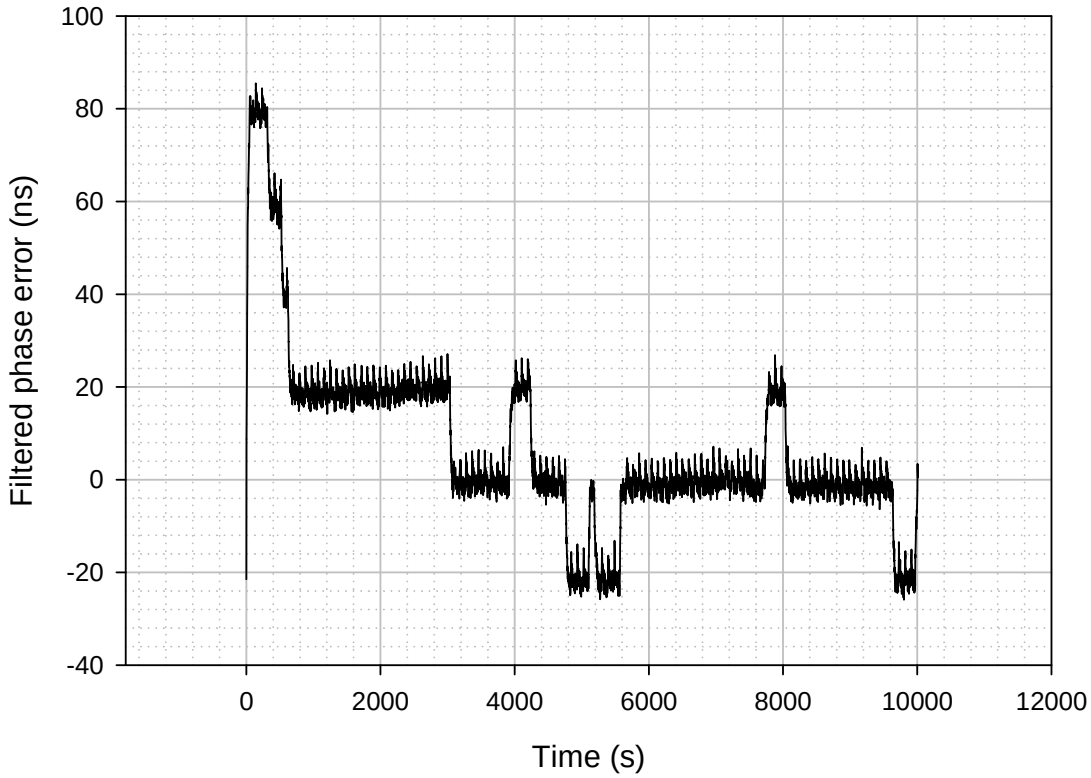
Case 2-125, Node 6 – Filtered Phase Error

Case 2-125,Node 6
Filtered phase error
Sync Interval = 0.125 s
Pdelay Interval = 1.0 s
Endpoint filter BW = 0.01 Hz
Local oscillator tolerance = +/- 5 ppm
(frequency offsets initialized randomly within tolerance range)



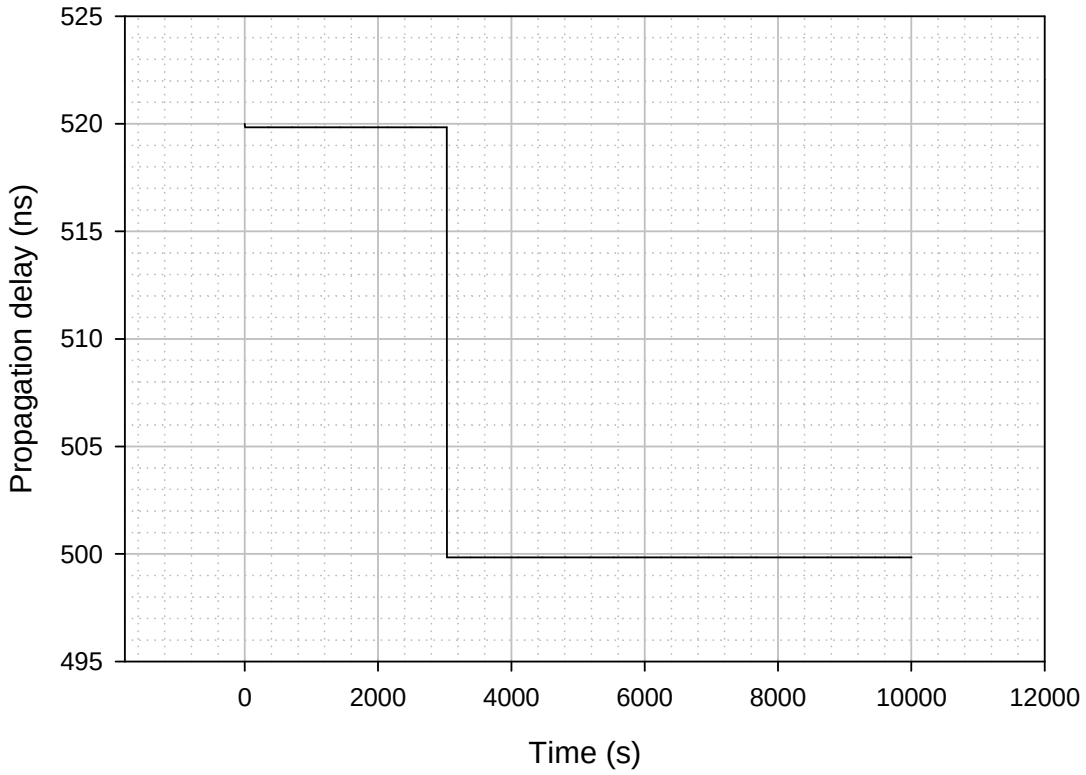
Case 2-125, Node 7 – Filtered Phase Error

Case 2-125,Node 7
Filtered phase error
Sync Interval = 0.125 s
Pdelay Interval = 1.0 s
Endpoint filter BW = 0.01 Hz
Local oscillator tolerance = +/- 5 ppm
(frequency offsets initialized randomly within tolerance range)



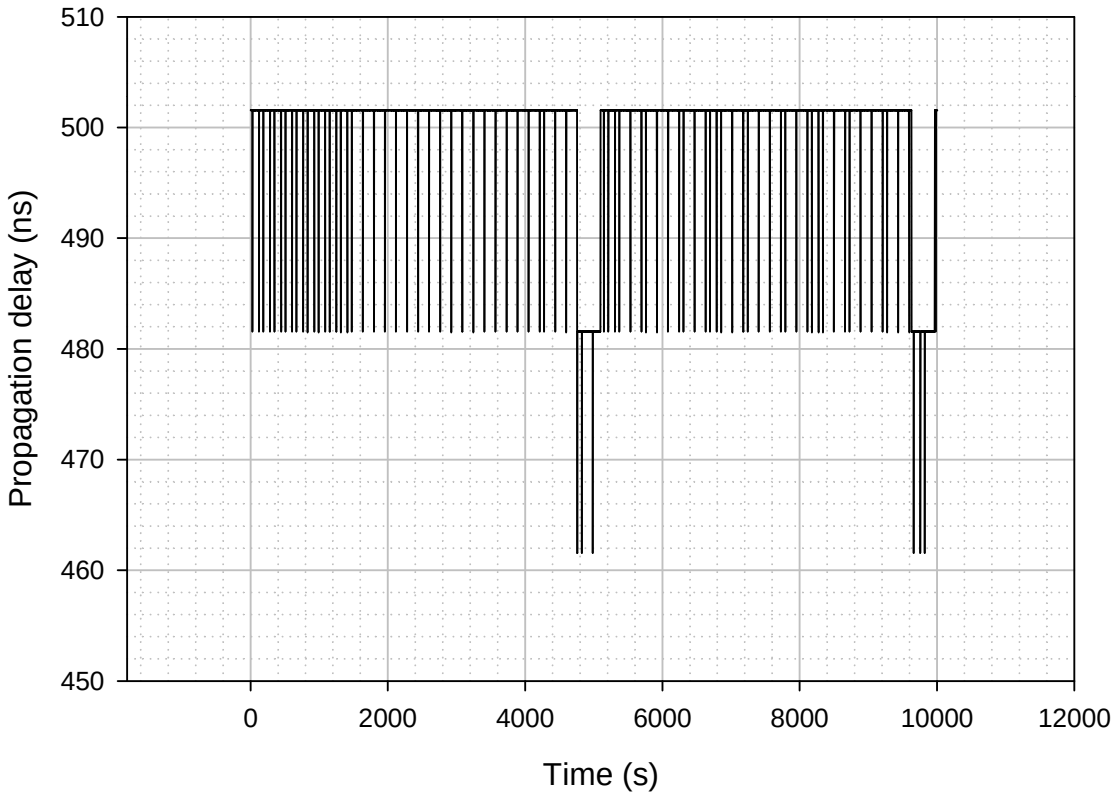
Case 2-125, Node 1 to 2 Propagation Delay

Case 2-125,Node 1 to 2 propagation delay
(after initialization)
Sync Interval = 0.125 s
Pdelay Interval = 1.0 s
Endpoint filter BW = 0.01 Hz
Local oscillator tolerance = +/- 5 ppm
(frequency offsets initialized randomly within tolerance range)



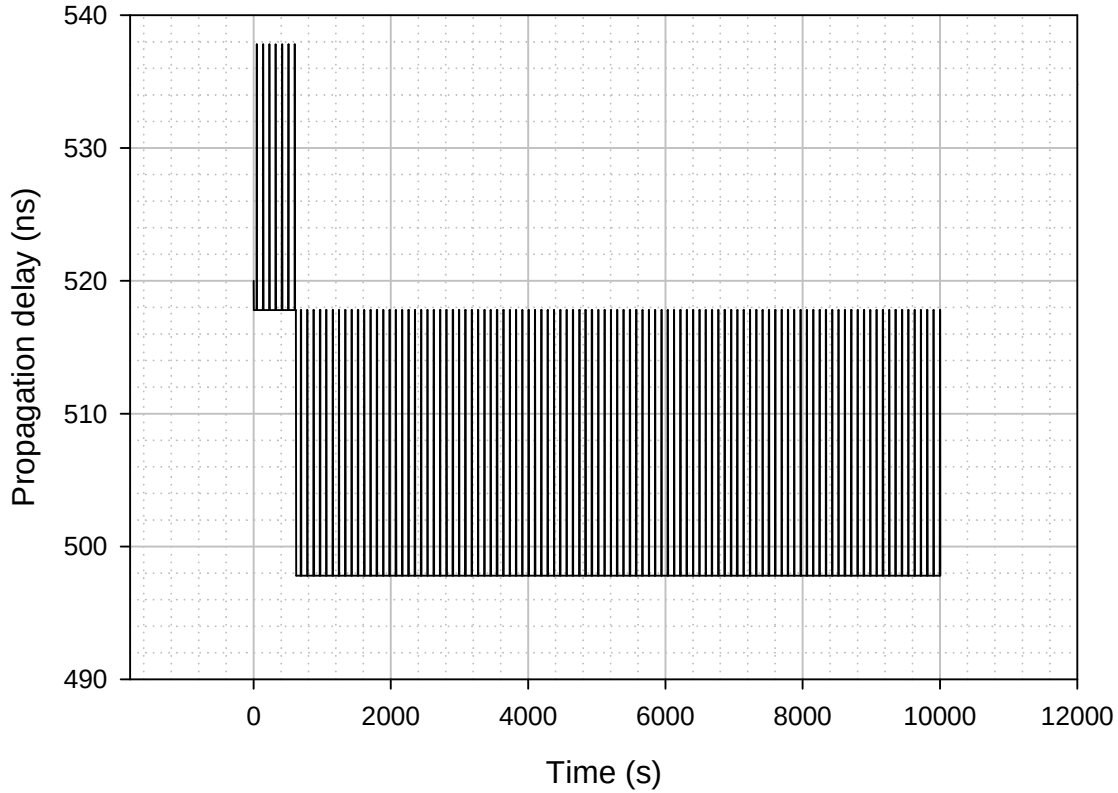
Case 2-125, Node 2 to 3 Propagation Delay

Case 2-125,Node 2 to 3 propagation delay
(after initialization)
Sync Interval = 0.125 s
Pdelay Interval = 1.0 s
Endpoint filter BW = 0.01 Hz
Local oscillator tolerance = +/- 5 ppm
(frequency offsets initialized randomly within tolerance range)



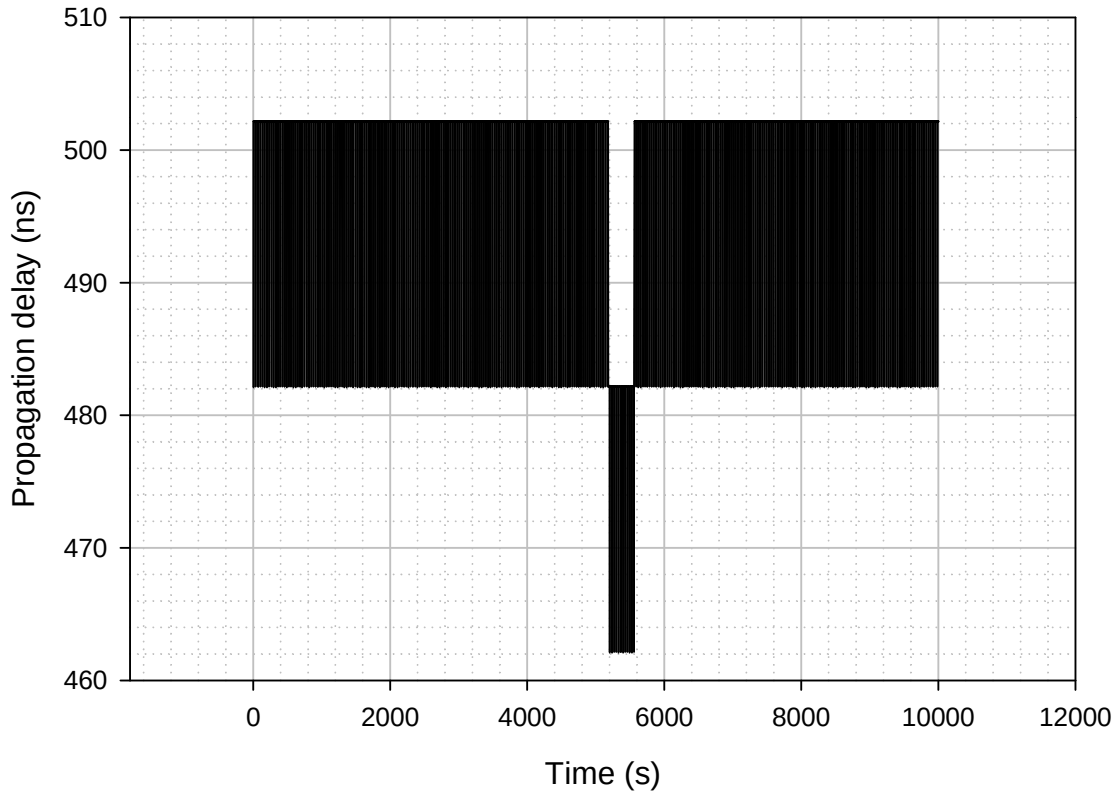
Case 2-125, Node 3 to 4 Propagation Delay

Case 2-125,Node 3 to 4 propagation delay
(after initialization)
Sync Interval = 0.125 s
Pdelay Interval = 1.0 s
Endpoint filter BW = 0.01 Hz
Local oscillator tolerance = +/- 5 ppm
(frequency offsets initialized randomly within tolerance range)



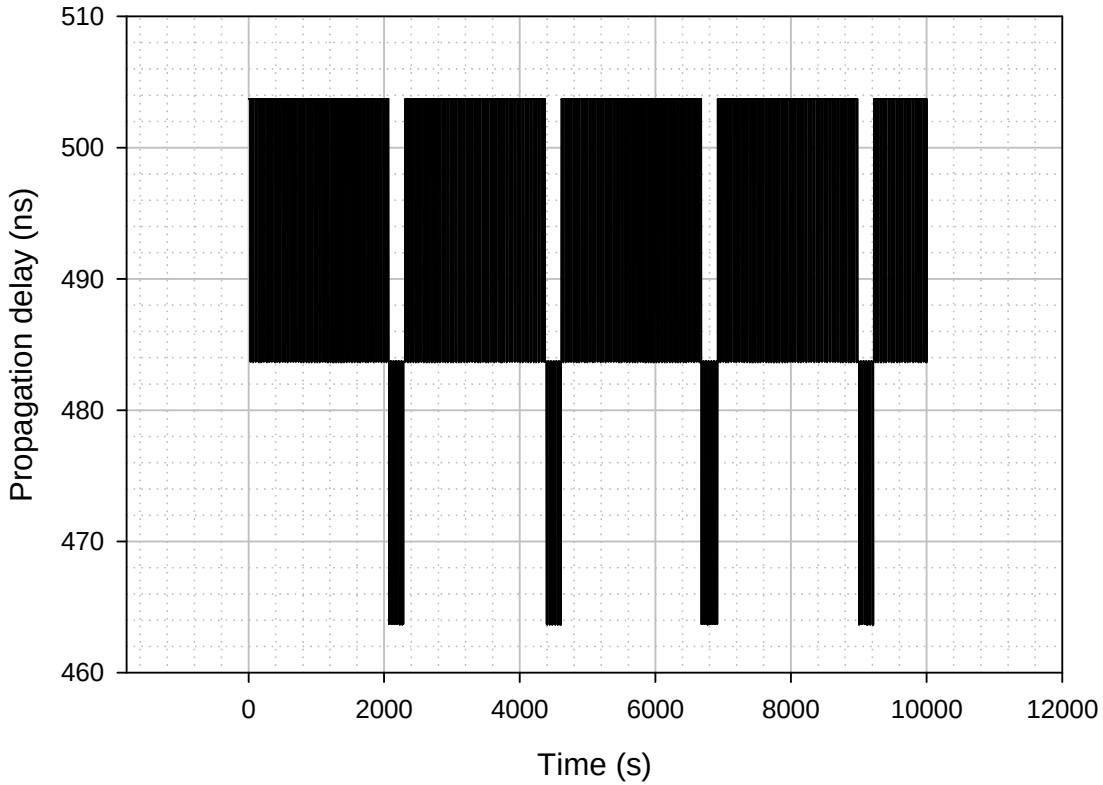
Case 2-125, Node 4 to 5 Propagation Delay

Case 2-125,Node 4 to 5 propagation delay
(after initialization)
Sync Interval = 0.125 s
Pdelay Interval = 1.0 s
Endpoint filter BW = 0.01 Hz
Local oscillator tolerance = +/- 5 ppm
(frequency offsets initialized randomly within tolerance range)



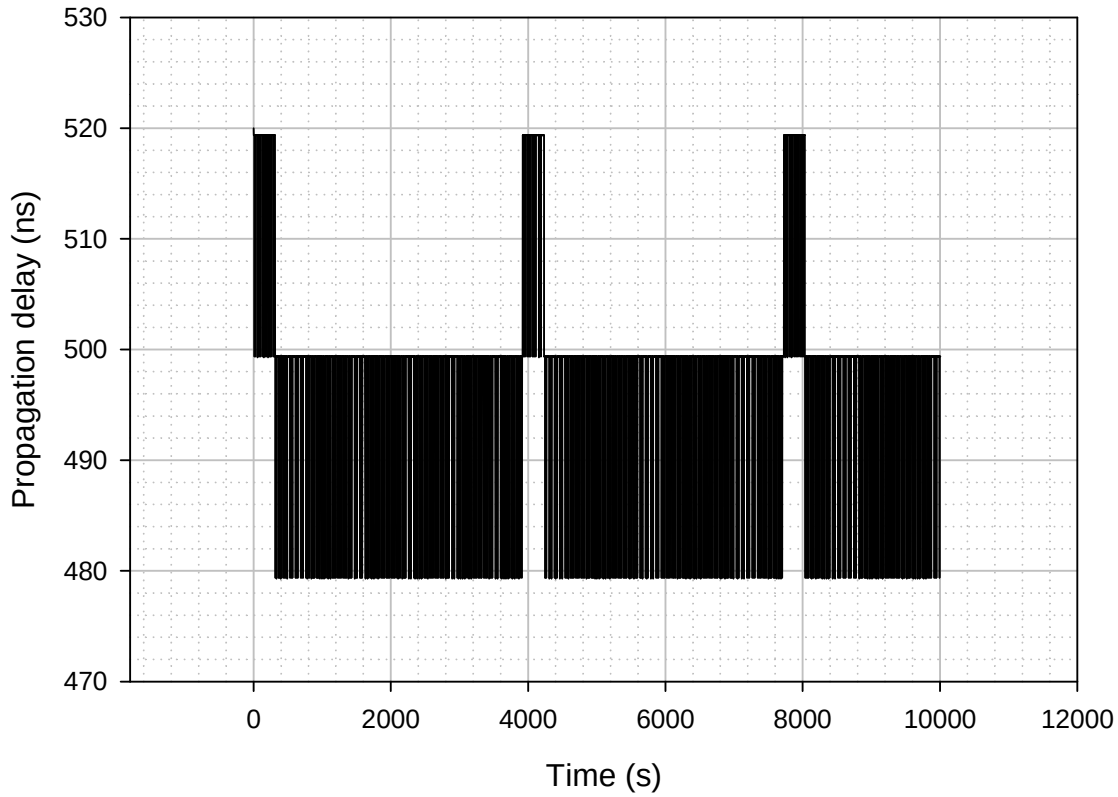
Case 2-125, Node 5 to 6 Propagation Delay

Case 2-125,Node 5 to 6 propagation delay
(after initialization)
Sync Interval = 0.125 s
Pdelay Interval = 1.0 s
Endpoint filter BW = 0.01 Hz
Local oscillator tolerance = +/- 5 ppm
(frequency offsets initialized randomly within tolerance range)



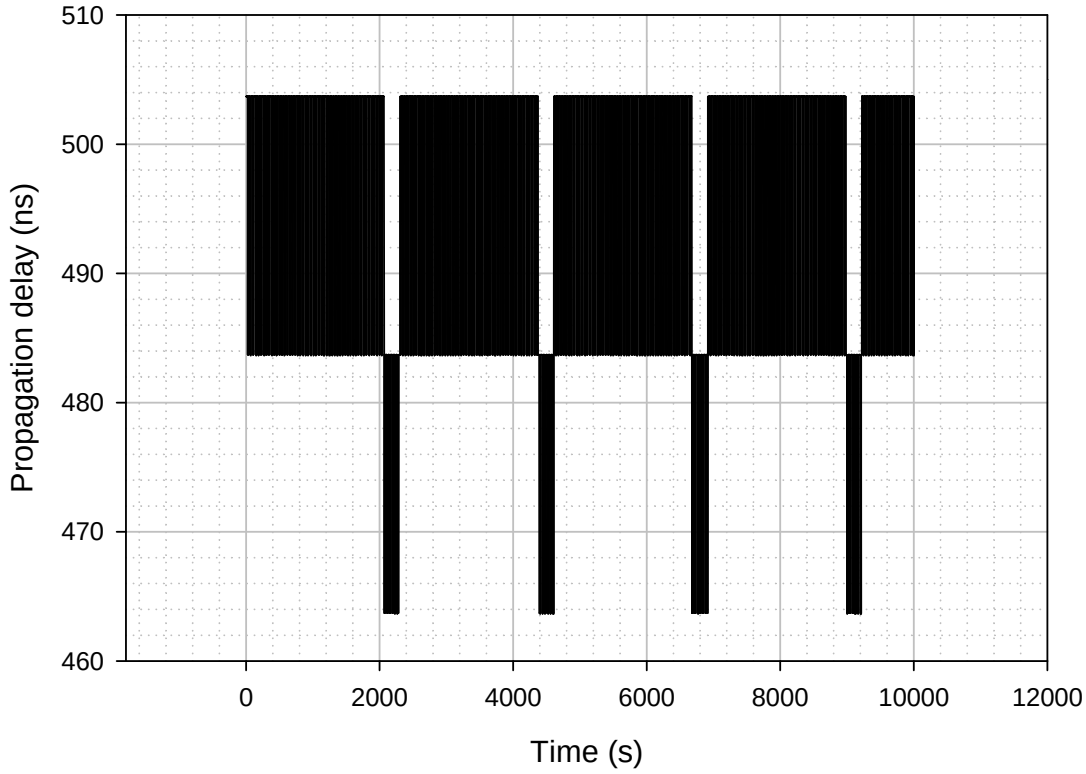
Case 2-125, Node 6 to 7 Propagation Delay

Case 2-125,Node 6 to 7 propagation delay
(after initialization)
Sync Interval = 0.125 s
Pdelay Interval = 1.0 s
Endpoint filter BW = 0.01 Hz
Local oscillator tolerance = +/- 5 ppm
(frequency offsets initialized randomly within tolerance range)



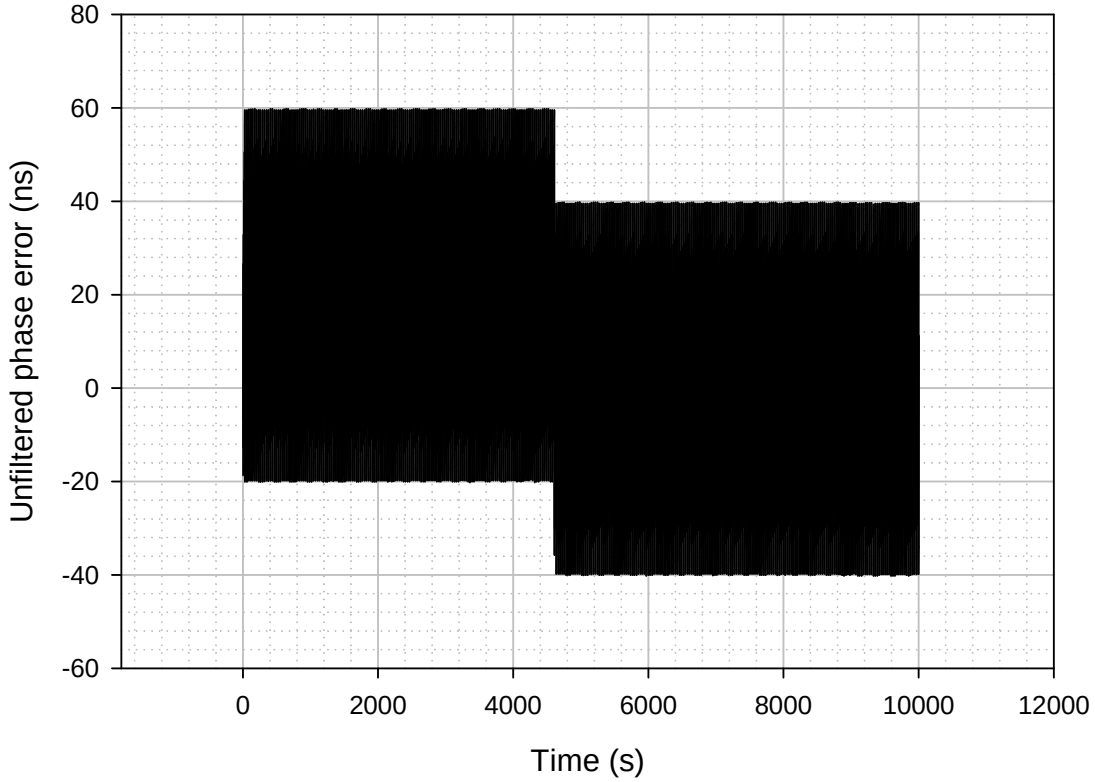
Case 2-125, Node 7 to 8 Propagation Delay

Case 2-125,Node 7 to 8 propagation delay
(after initialization)
Sync Interval = 0.125 s
Pdelay Interval = 1.0 s
Endpoint filter BW = 0.01 Hz
Local oscillator tolerance = +/- 5 ppm
(frequency offsets initialized randomly within tolerance range)



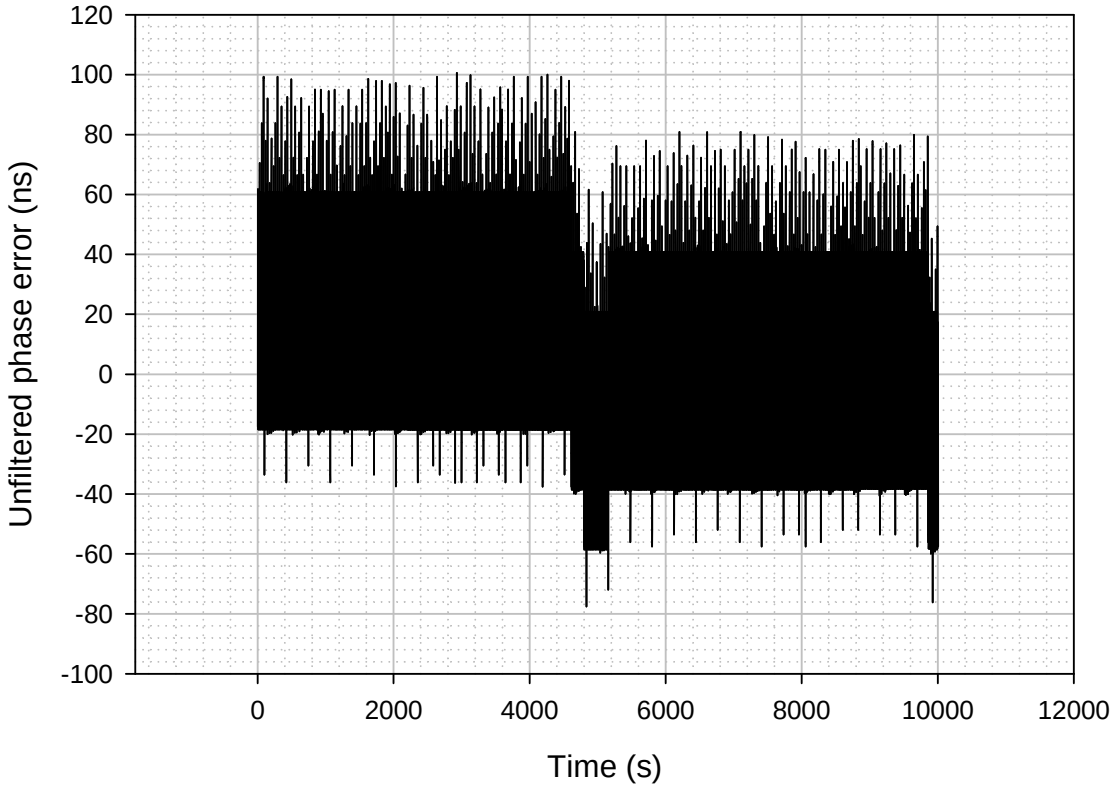
Case 2-250, Node 2 – Unfiltered Phase Error after initial transient

Case 2-250,Node 2
Unfiltered phase error, initial transient removed
Sync Interval = 0.250 s
Pdelay Interval = 2.0 s
Endpoint filter BW = 0.01 Hz
Local oscillator tolerance = +/- 5 ppm
(frequency offsets initialized randomly within tolerance range)



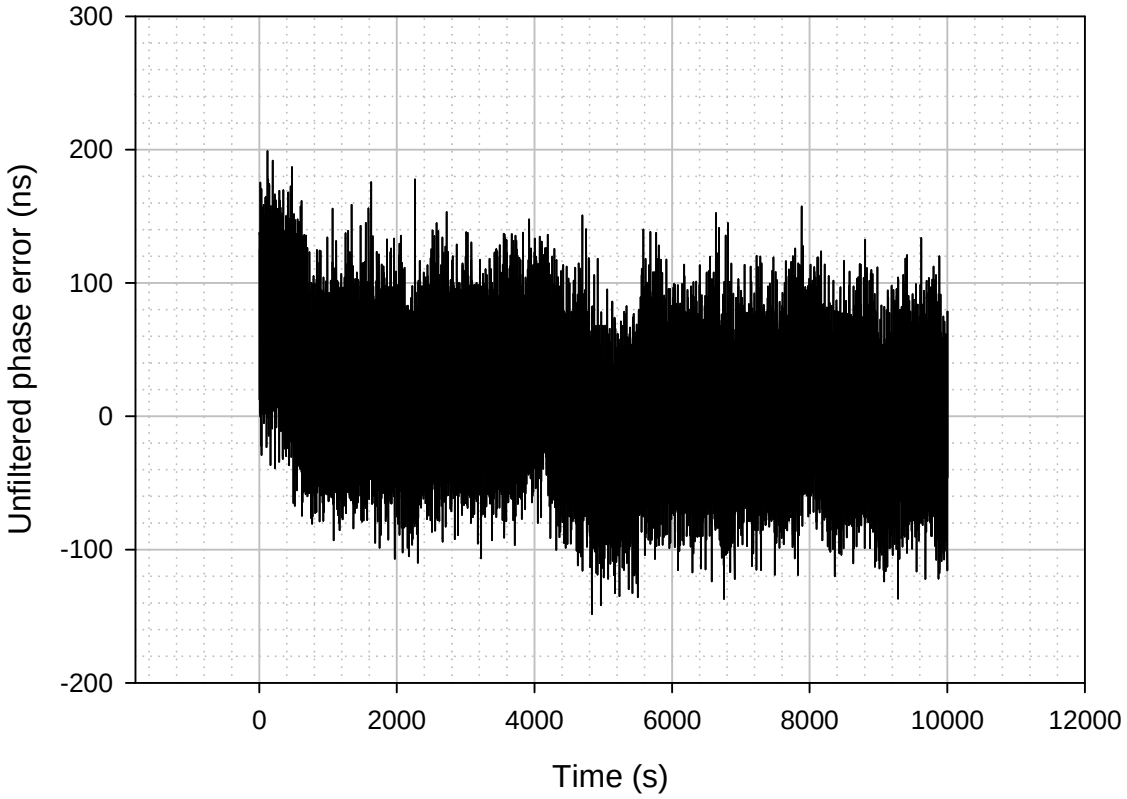
Case 2-250, Node 3 – Unfiltered Phase Error, after initial transient

Case 2-250,Node 3
Unfiltered phase error, initial transient removed
Sync Interval = 0.250 s
Pdelay Interval = 2.0 s
Endpoint filter BW = 0.01 Hz
Local oscillator tolerance = +/- 5 ppm
(frequency offsets initialized randomly within tolerance range)



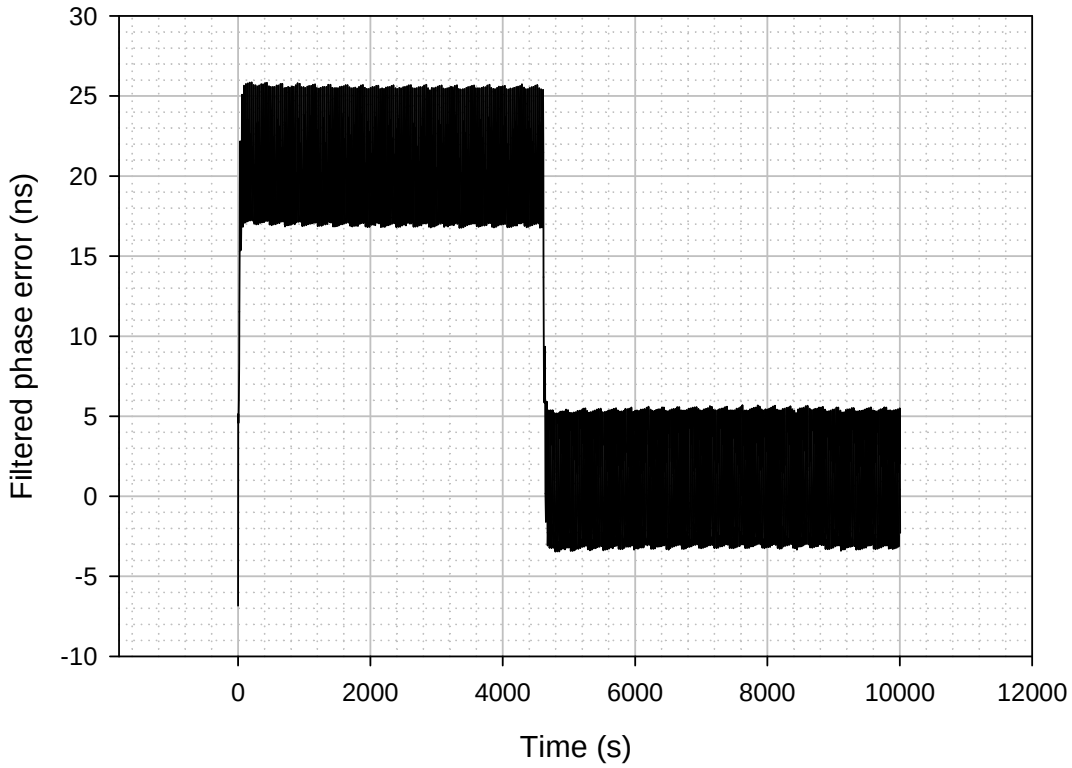
Case 2-250, Node 8 – Unfiltered Phase Error, after initial transient

Case 2-250,Node 8
Unfiltered phase error, initial transient removed
Sync Interval = 0.250 s
Pdelay Interval = 2.0 s
Endpoint filter BW = 0.01 Hz
Local oscillator tolerance = +/- 5 ppm
(frequency offsets initialized randomly within tolerance range)



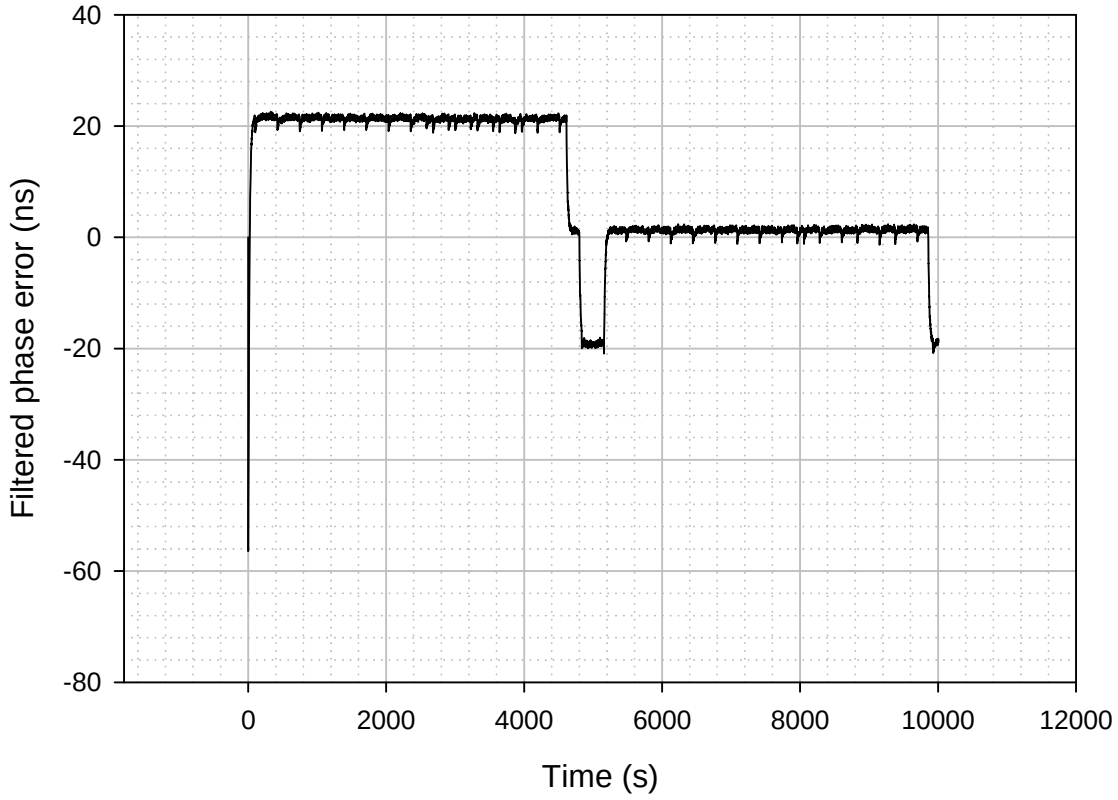
Case 2-250, Node 2 – Filtered Phase Error

Case 2-250,Node 2
Filtered phase error
Sync Interval = 0.250 s
Pdelay Interval = 2.0 s
Endpoint filter BW = 0.01 Hz
Local oscillator tolerance = +/- 5 ppm
(frequency offsets initialized randomly within tolerance range)



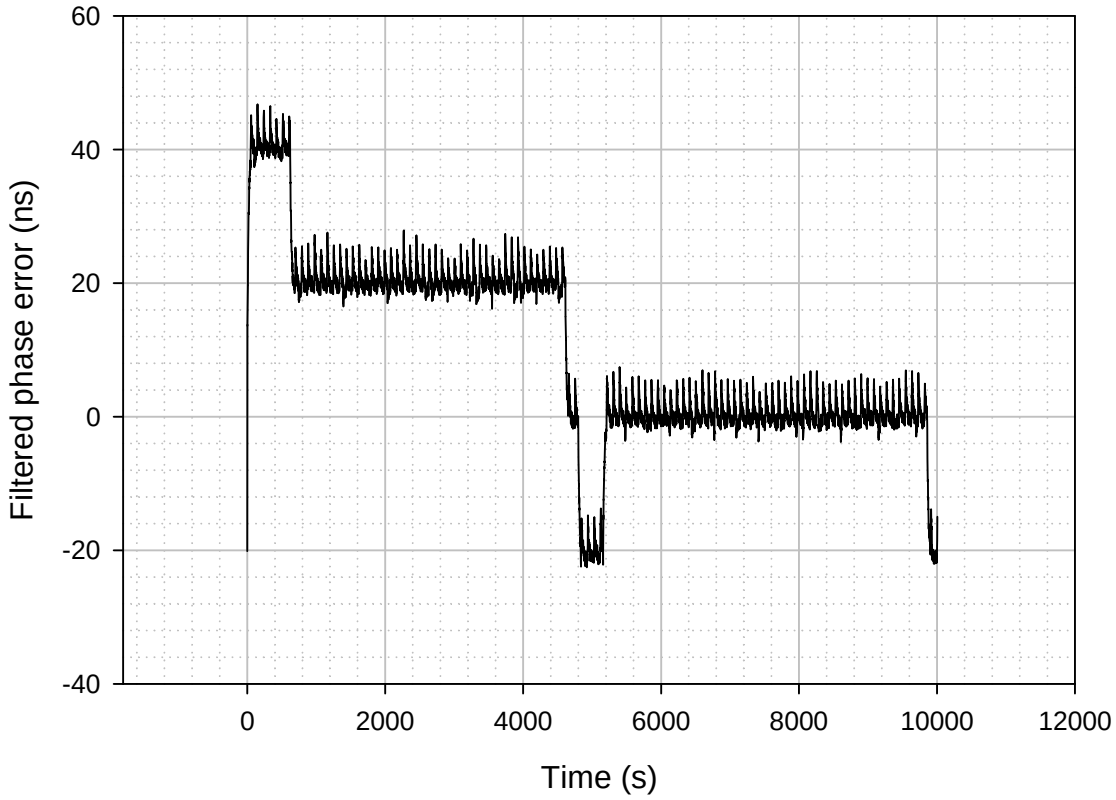
Case 2-250, Node 3 – Filtered Phase Error

Case 2-250,Node 3
Filtered phase error
Sync Interval = 0.250 s
Pdelay Interval = 2.0 s
Endpoint filter BW = 0.01 Hz
Local oscillator tolerance = +/- 5 ppm
(frequency offsets initialized randomly within tolerance range)



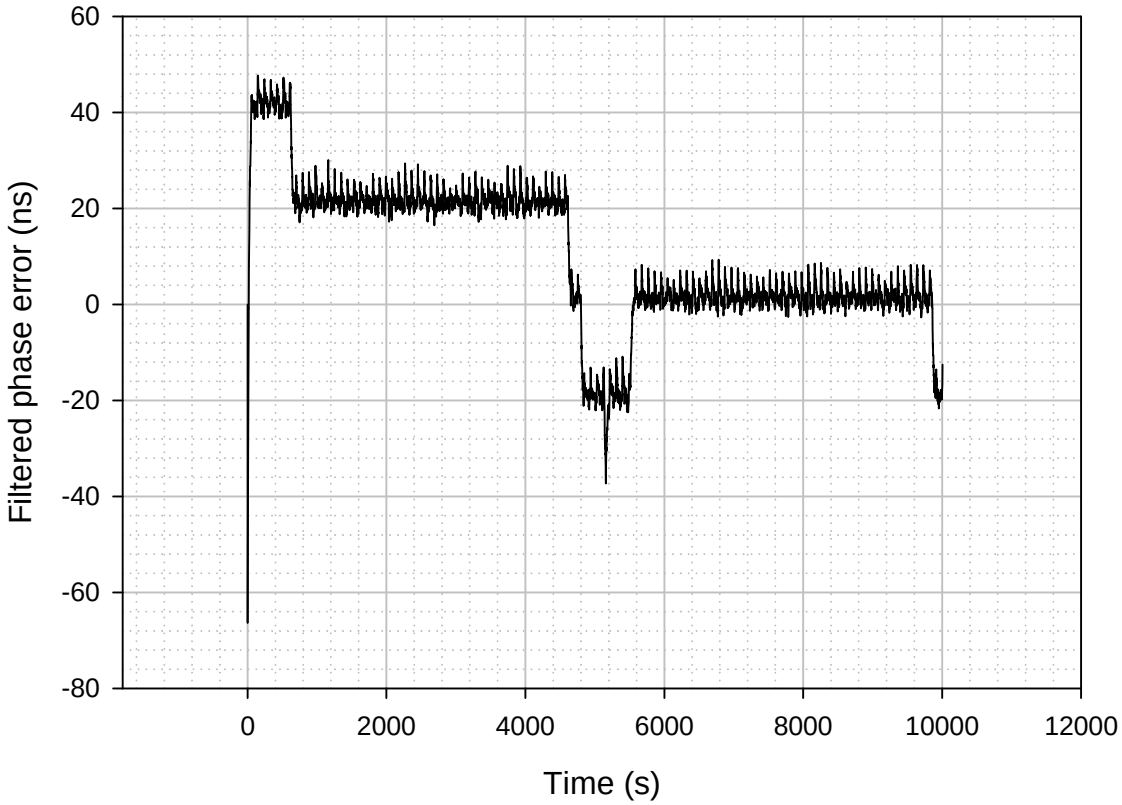
Case 2-250, Node 4 – Filtered Phase Error

Case 2-250,Node 4
Filtered phase error
Sync Interval = 0.250 s
Pdelay Interval = 2.0 s
Endpoint filter BW = 0.01 Hz
Local oscillator tolerance = +/- 5 ppm
(frequency offsets initialized randomly within tolerance range)



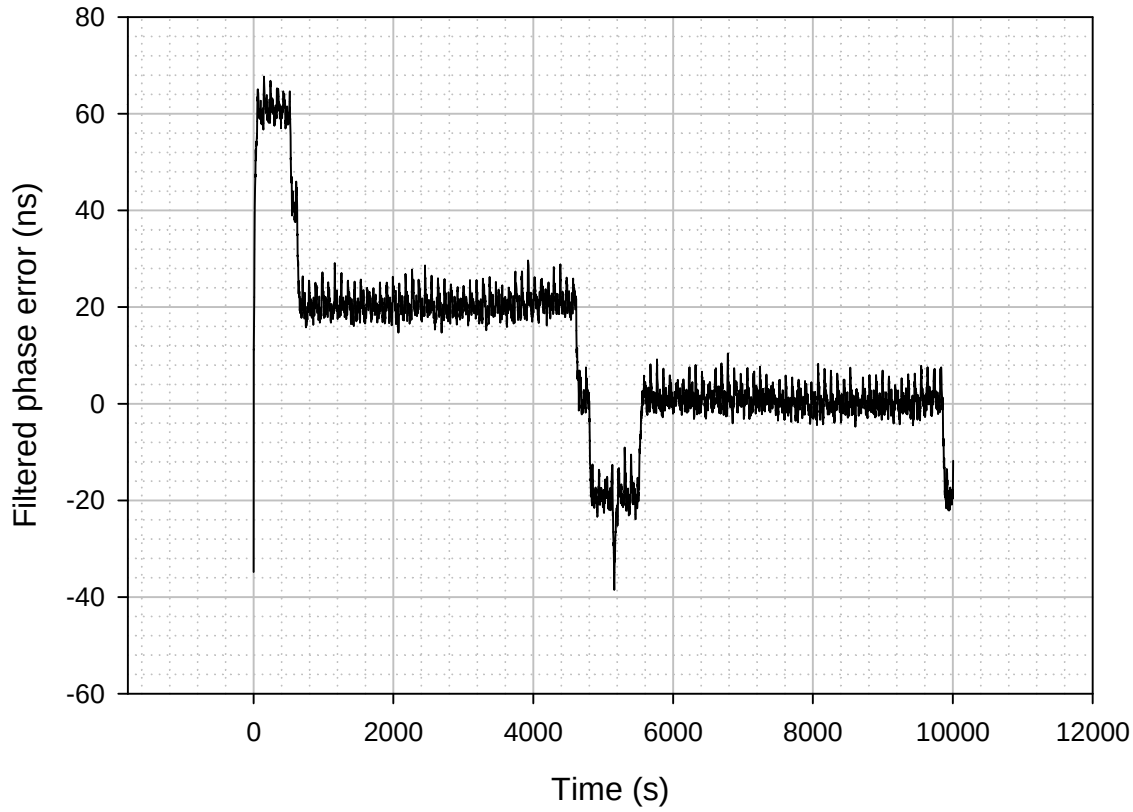
Case 2-250, Node 5 – Filtered Phase Error

Case 2-250,Node 5
Filtered phase error
Sync Interval = 0.250 s
Pdelay Interval = 2.0 s
Endpoint filter BW = 0.01 Hz
Local oscillator tolerance = +/- 5 ppm
(frequency offsets initialized randomly within tolerance range)



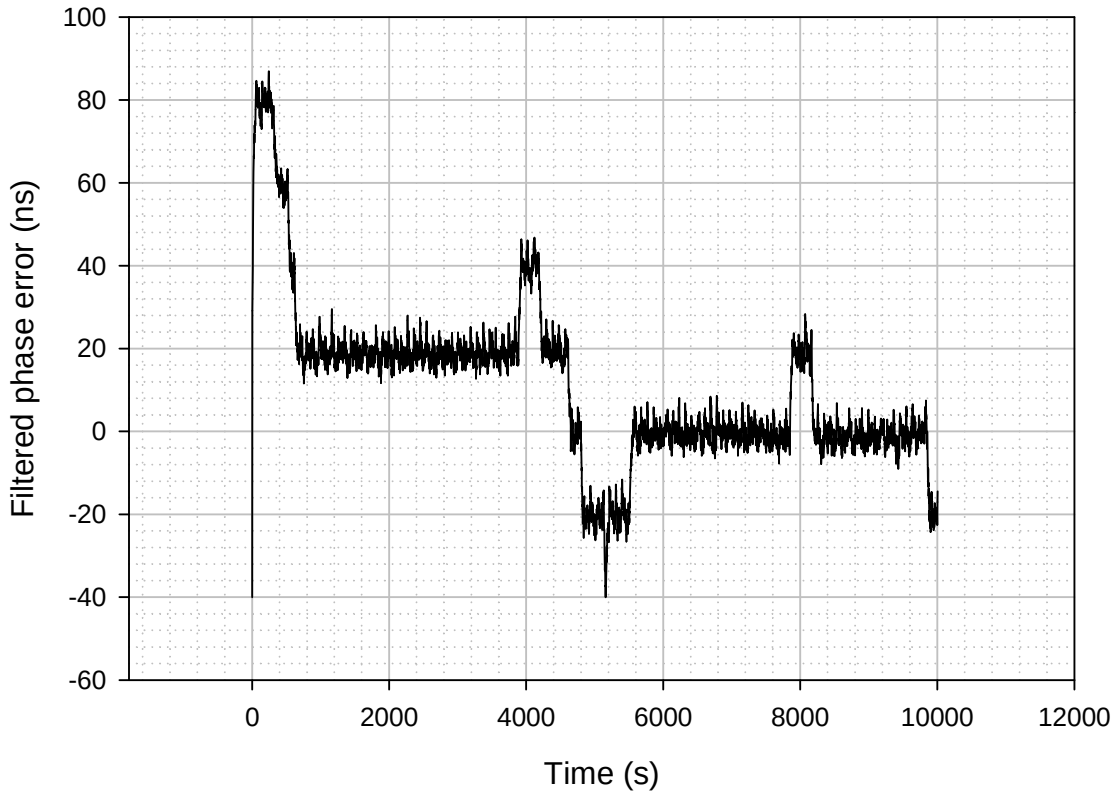
Case 2-250, Node 6 – Filtered Phase Error

Case 2-250,Node 6
Filtered phase error
Sync Interval = 0.250 s
Pdelay Interval = 2.0 s
Endpoint filter BW = 0.01 Hz
Local oscillator tolerance = +/- 5 ppm
(frequency offsets initialized randomly within tolerance range)



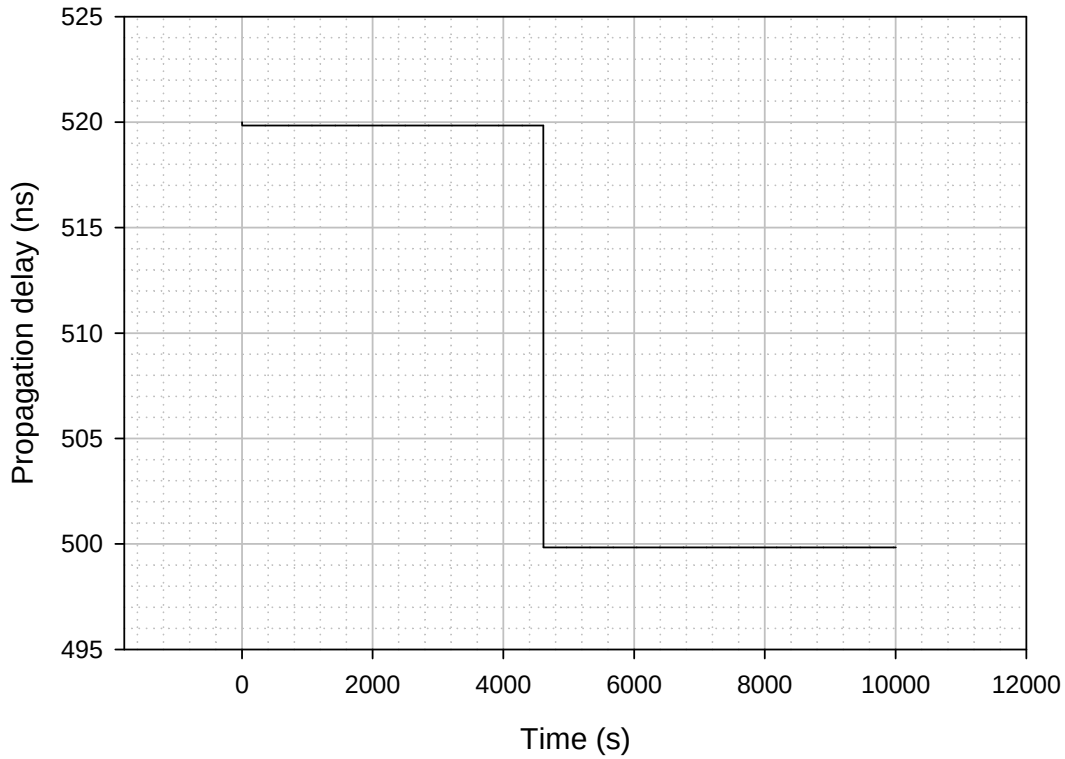
Case 2-250, Node 7 – Filtered Phase Error

Case 2-250,Node 7
Filtered phase error
Sync Interval = 0.250 s
Pdelay Interval = 2.0 s
Endpoint filter BW = 0.01 Hz
Local oscillator tolerance = +/- 5 ppm
(frequency offsets initialized randomly within tolerance range)



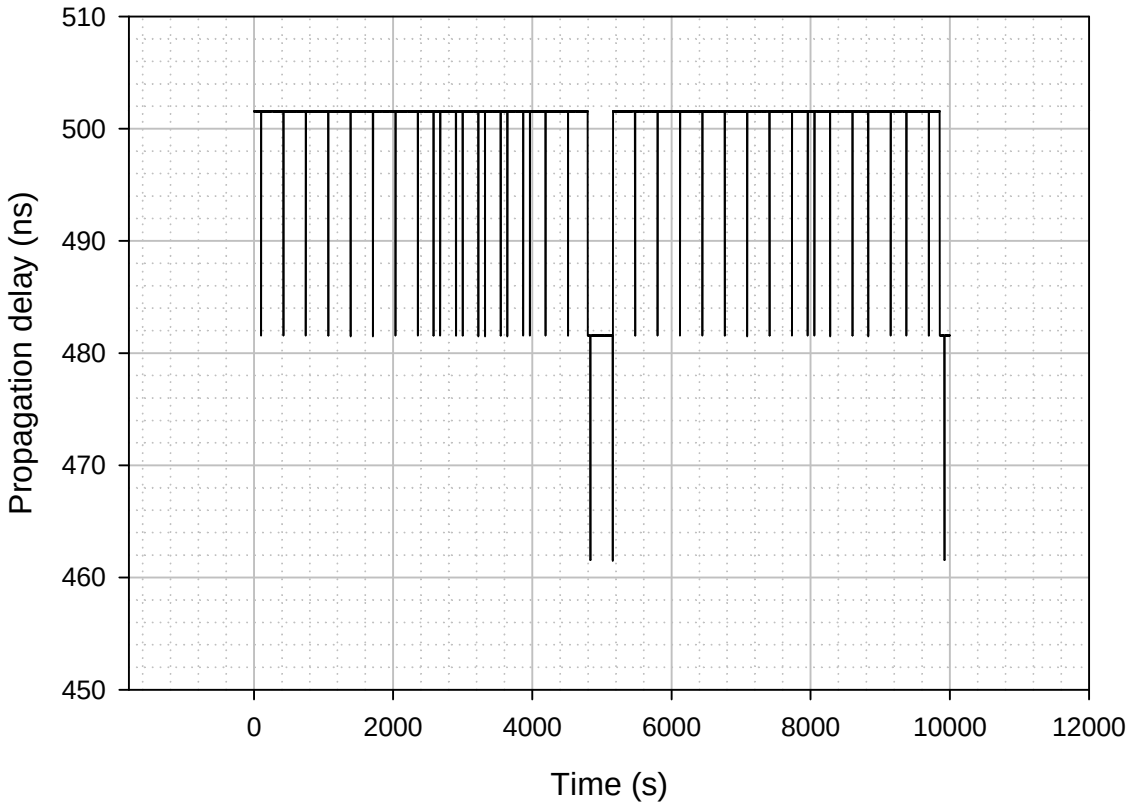
Case 2-250, Node 1 to 2 Propagation Delay

Case 2-250,Node 1 to 2 propagation delay
(after initialization)
Sync Interval = 0.250 s
Pdelay Interval = 2.0 s
Endpoint filter BW = 0.01 Hz
Local oscillator tolerance = +/- 5 ppm
(frequency offsets initialized randomly within tolerance range)



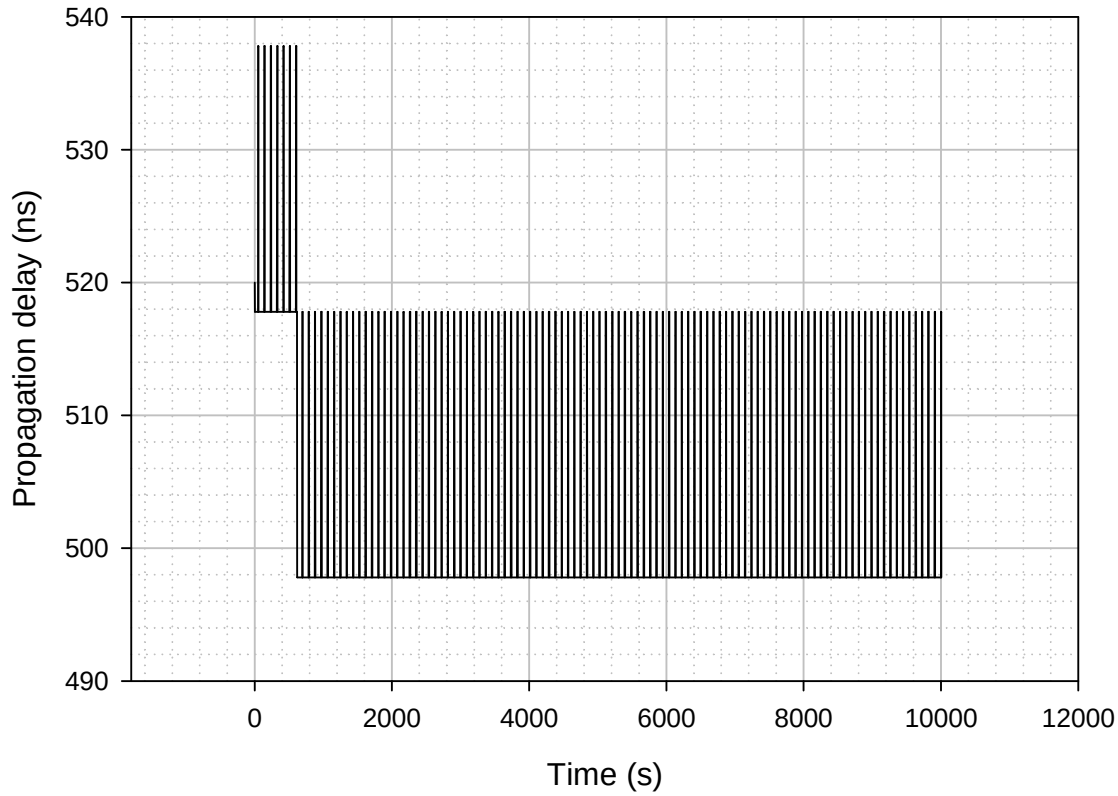
Case 2-250, Node 2 to 3 Propagation Delay

Case 2-250,Node 2 to 3 propagation delay
(after initialization)
Sync Interval = 0.250 s
Pdelay Interval = 2.0 s
Endpoint filter BW = 0.01 Hz
Local oscillator tolerance = +/- 5 ppm
(frequency offsets initialized randomly within tolerance range)



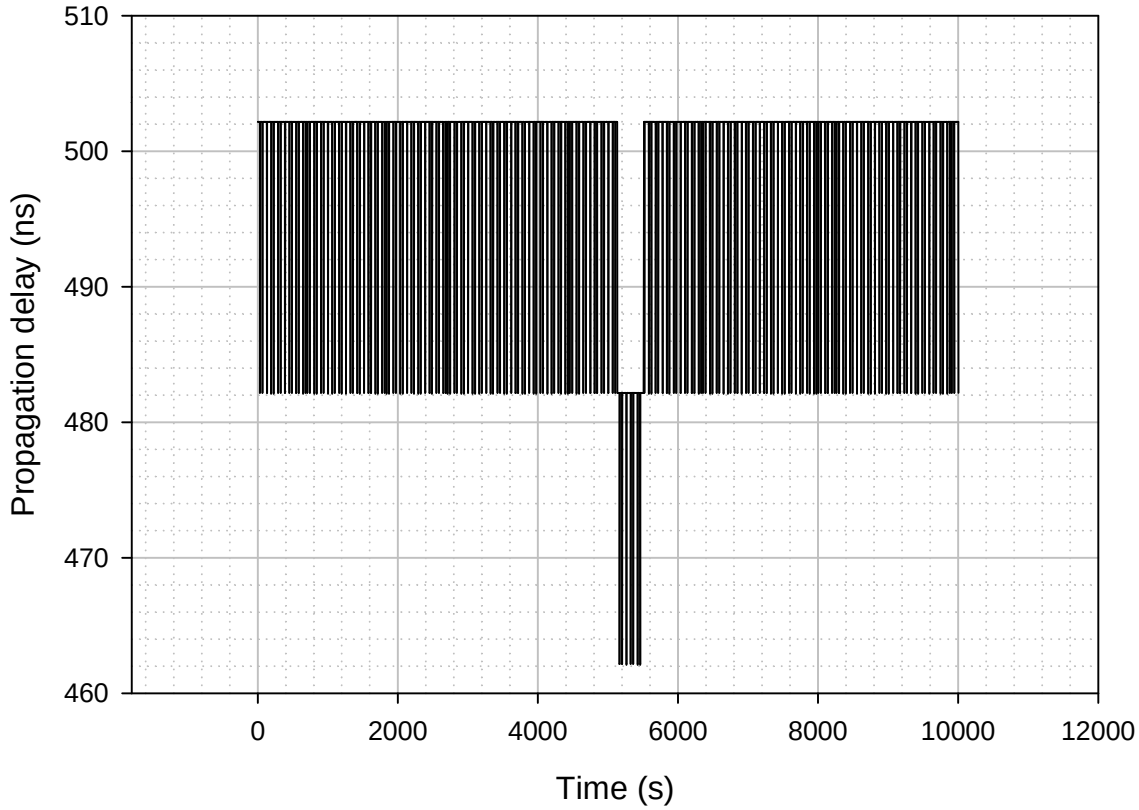
Case 2-250, Node 3 to 4 Propagation Delay

Case 2-250,Node 3 to 4 propagation delay
(after initialization)
Sync Interval = 0.250 s
Pdelay Interval = 2.0 s
Endpoint filter BW = 0.01 Hz
Local oscillator tolerance = +/- 5 ppm
(frequency offsets initialized randomly within tolerance range)



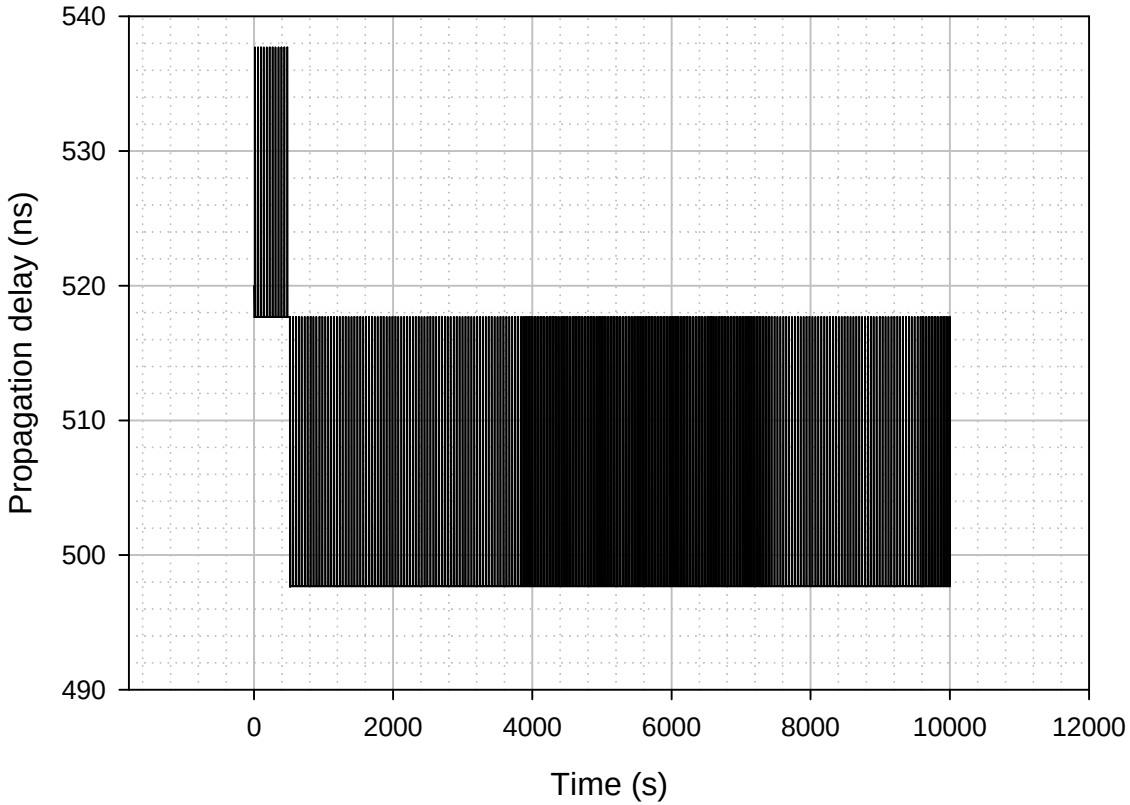
Case 2-250, Node 4 to 5 Propagation Delay

Case 2-250,Node 4 to 5 propagation delay
(after initialization)
Sync Interval = 0250 s
Pdelay Interval = 2.0 s
Endpoint filter BW = 0.01 Hz
Local oscillator tolerance = +/- 5 ppm
(frequency offsets initialized randomly within tolerance range)



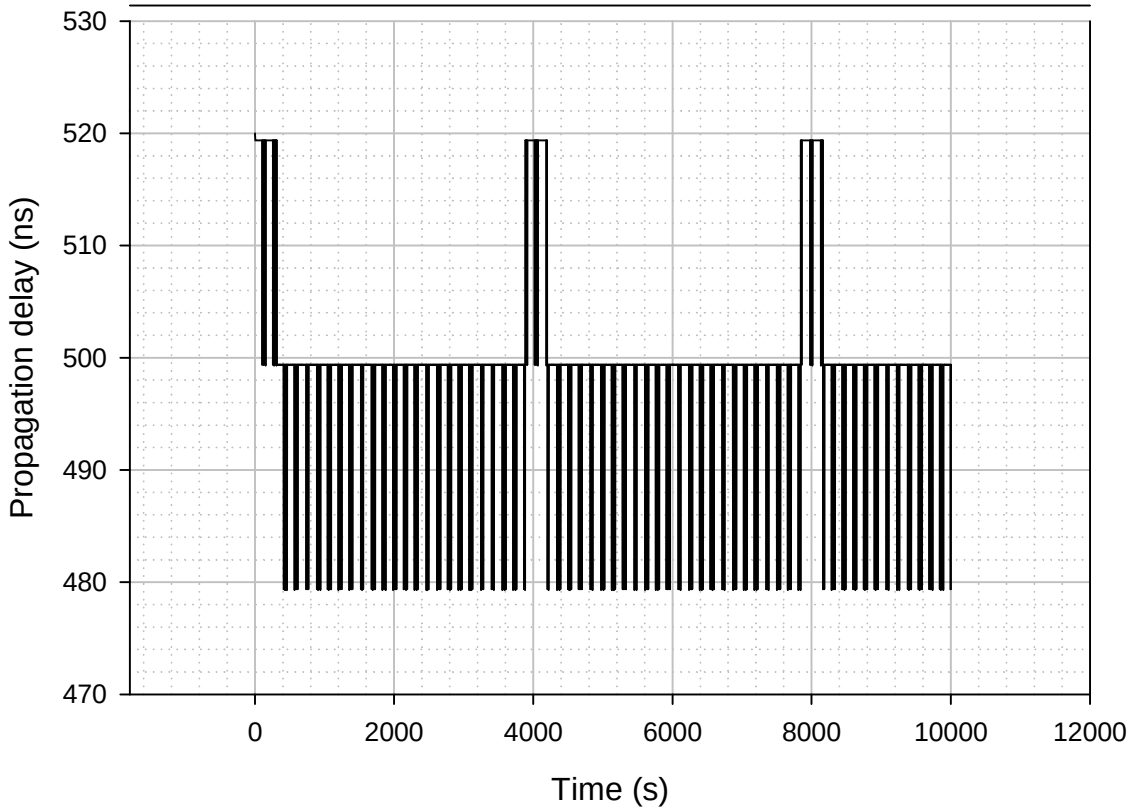
Case 2-250, Node 5 to 6 Propagation Delay

Case 2-250,Node 5 to 6 propagation delay
(after initialization)
Sync Interval = 0.250 s
Pdelay Interval = 2.0 s
Endpoint filter BW = 0.01 Hz
Local oscillator tolerance = +/- 5 ppm
(frequency offsets initialized randomly within tolerance range)



Case 2-250, Node 6 to 7 Propagation Delay

Case 2-250,Node 6 to 7 propagation delay
(after initialization)
Sync Interval = 0.250 s
Pdelay Interval = 2.0 s
Endpoint filter BW = 0.01 Hz
Local oscillator tolerance = +/- 5 ppm
(frequency offsets initialized randomly within tolerance range)



Case 2-250, Node 7 to 8 Propagation Delay

Case 2-250,Node 7 to 8 propagation delay
(after initialization)
Sync Interval = 0.250 s
Pdelay Interval = 2.0 s
Endpoint filter BW = 0.01 Hz
Local oscillator tolerance = +/- 5 ppm
(frequency offsets initialized randomly within tolerance range)