60802 Time Sync – Mean Link Delay Averaging & Normative Requirements

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Version 3

References

[1] David McCall, "60802 Time Synchronisation – Monte Carlo Analysis: 100-hop Model, "Linear" Clock Drift, NRR Accumulation Overview & Details, Including Equations – v2", 60802 contribution, Sept 2022

[2] David McCall "IEC/IEEE 60802 Contribution – Time Sync Informative Annex – v6", 60802 Contribution, Sept 2023

[3] Geoff Garner "New Multiple Replication 60802 Time Domain Simulation Results for Cases with Drift Tracking Algorithms and PLL Noise Generation", 60802 Contribution, Sept 2023

Content

- Background
- 60802's recommended meanLinkDelay Algorithm
  - Startup behaviour
  - Dos and Don'ts
- Implications for Simulations – Recent vs Future
  - Time Series
    - IIR Factor of 100 vs 1000
    - Settling time of 50s
    - Implications & Recommendations
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    - Implications & Recommendations
- Normative Requirements

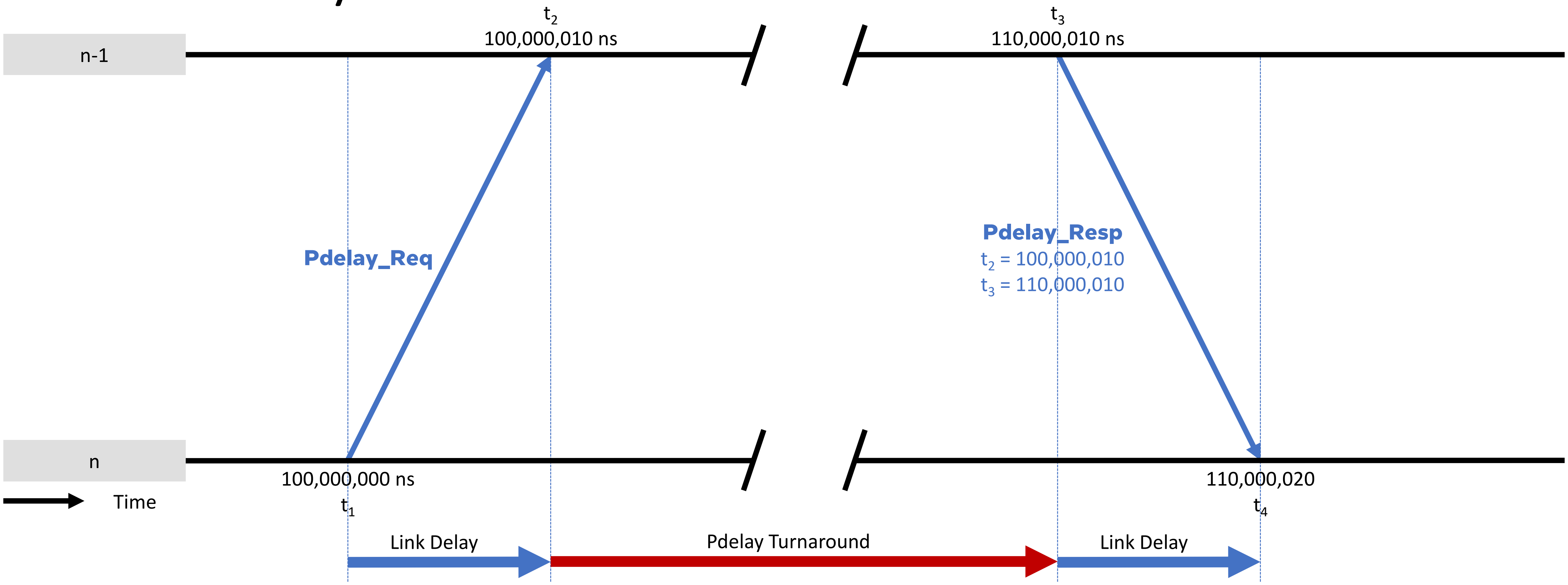
Background

- 802.1AS-2020 assumes meanLinkDelay and provides some informative language about approaches to averaging but no normative requirements
  - See IEEE 802.1AS Clause 11.2.1.
- Initial Monte Carlo simulations implemented a simple “% effective”
  - 90% effective removed 90% of the error
  - Even without the algorithm, meanLinkDelay error was much smaller than other factors, and almost entirely due to Timestamp Error
- More recent Monte Carlo simulations modelled 50 previous path delay measurements (for each node) and took an average
- Latest Time Series simulations implemented the recommended algorithm (from Annex D), but used a factor of 100 vs recommendation of 1000
- Additional, focused, simulations investigating behaviour of meanLinkDelay averaging would be useful…and are provided in this contribution.

Recommended meanLinkDelay Algorithm

From IEC/IEEE 60802, Annex D

Path Delay Measurement



$$mPathDelay = \frac{(t_4(x) - t_1(x)) - \frac{(t_3(x) - t_2(x))}{Neighbor\ Rate\ Ratio(x)}}{2} = 10\ \text{ns}$$

Mean Link Delay Averaging

$$mPathDelay(x) = \frac{(t_4 - t_1) - \frac{(t_3 - t_2)}{NRR}}{2}$$ ns

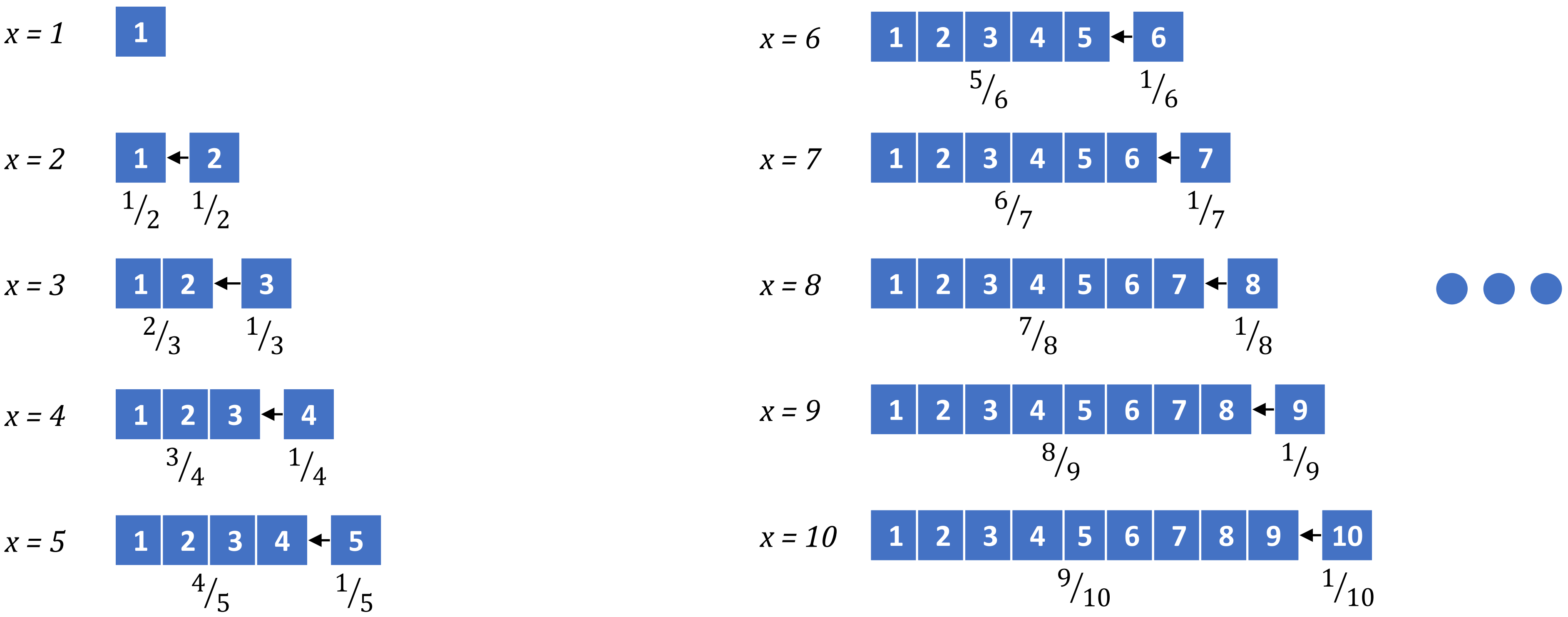
If $x = 1$

$$meanLinkDelay(x) = mPathDelay(x)$$ ns

If $x < 1000$ then α= $\frac{1}{x}$ else α= $\frac{1}{1000}$

$$meanLinkDelay(x) = \big((1-\alpha) \times meanLinkDelay(x-1)\big) + \alpha \times mPathDelay(x)$$ ns

Startup Behaviour – Recommended Algorithm



Two Simulation Types

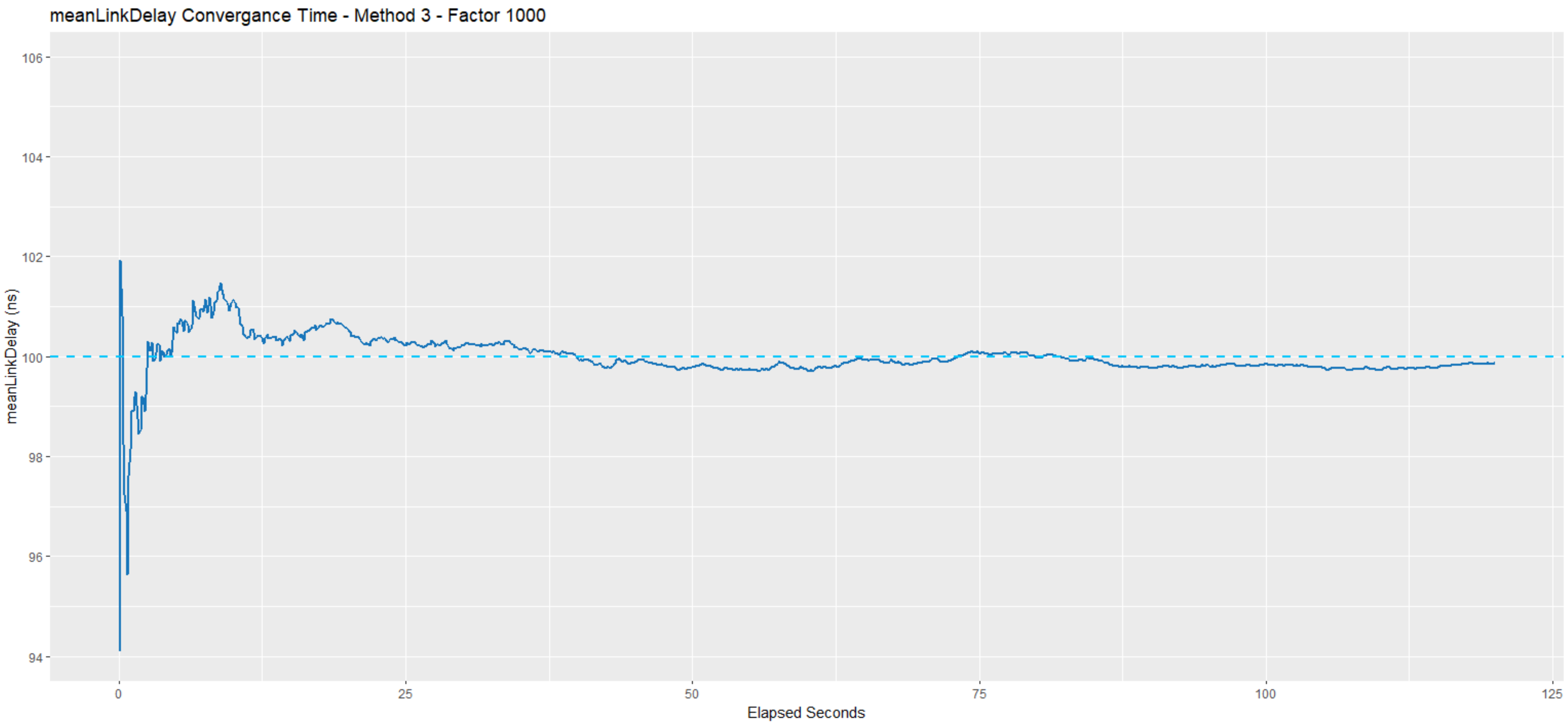
- Single Run
  - Plots progress of meanLinkDelay
- Multiple Runs
  - 100,000 runs
  - Plots progress of
    - Central 90% percentile
    - Min & Max
    - Mean ±6σ
  - Also…
    - Probability Distributions
    - QQ Plots

- Both versions…
  - Only model Timestamp Errors
  - TSGE: ±4 ns
  - DTSE: +6 ns
  - Actual Link Delay: 100 ns
  - Interval: 125 ms (no variation)

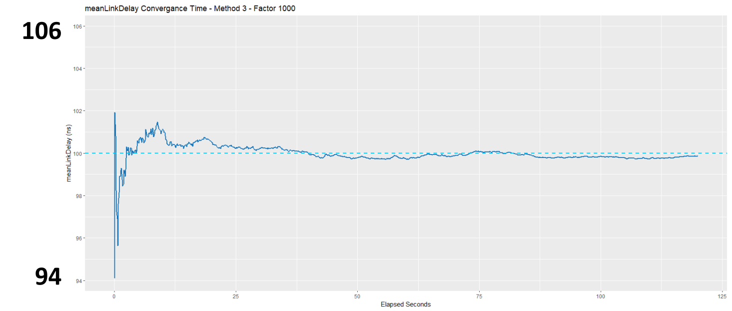
For normal distribution, one sample would fall outside ±6σ on average approximately every 500,000,000 samples. For a 125 ms interval that's approximately once every 2 years.

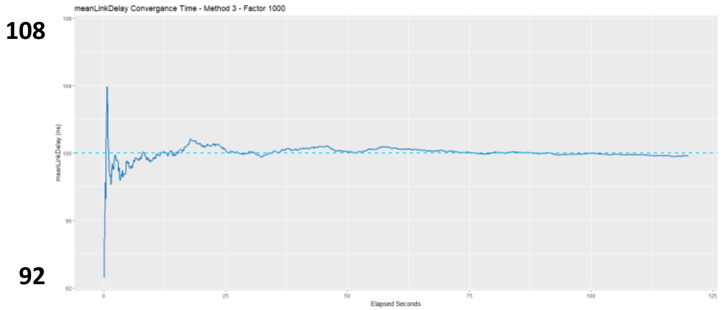
[This is true for a steady state…which this is not…but we'll come back to that.]

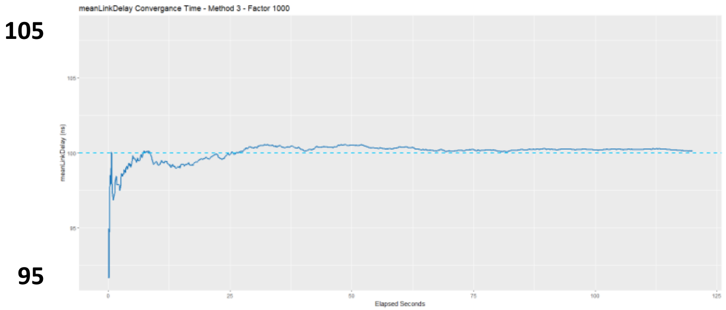
Single Run – 2 min

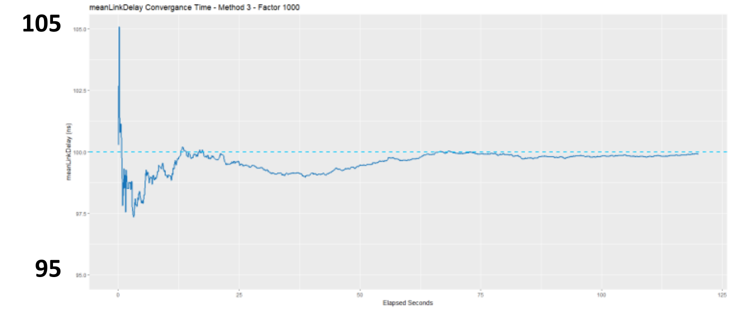


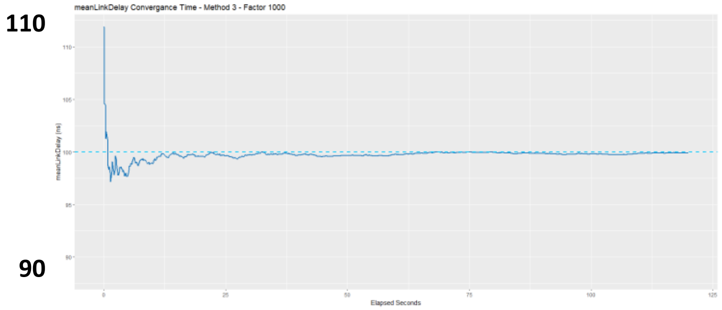
Single Run – 2 min

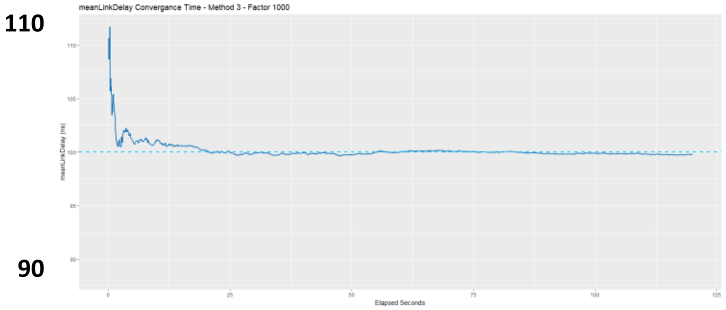


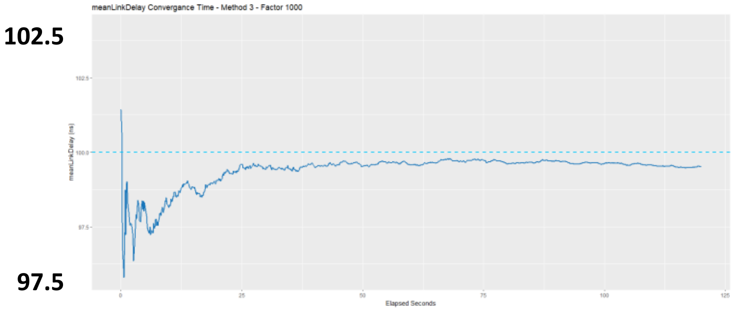


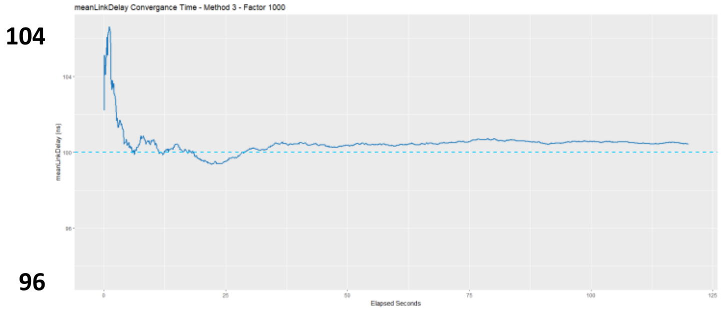


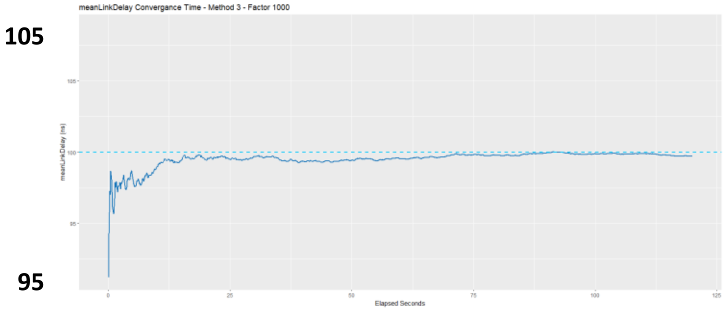




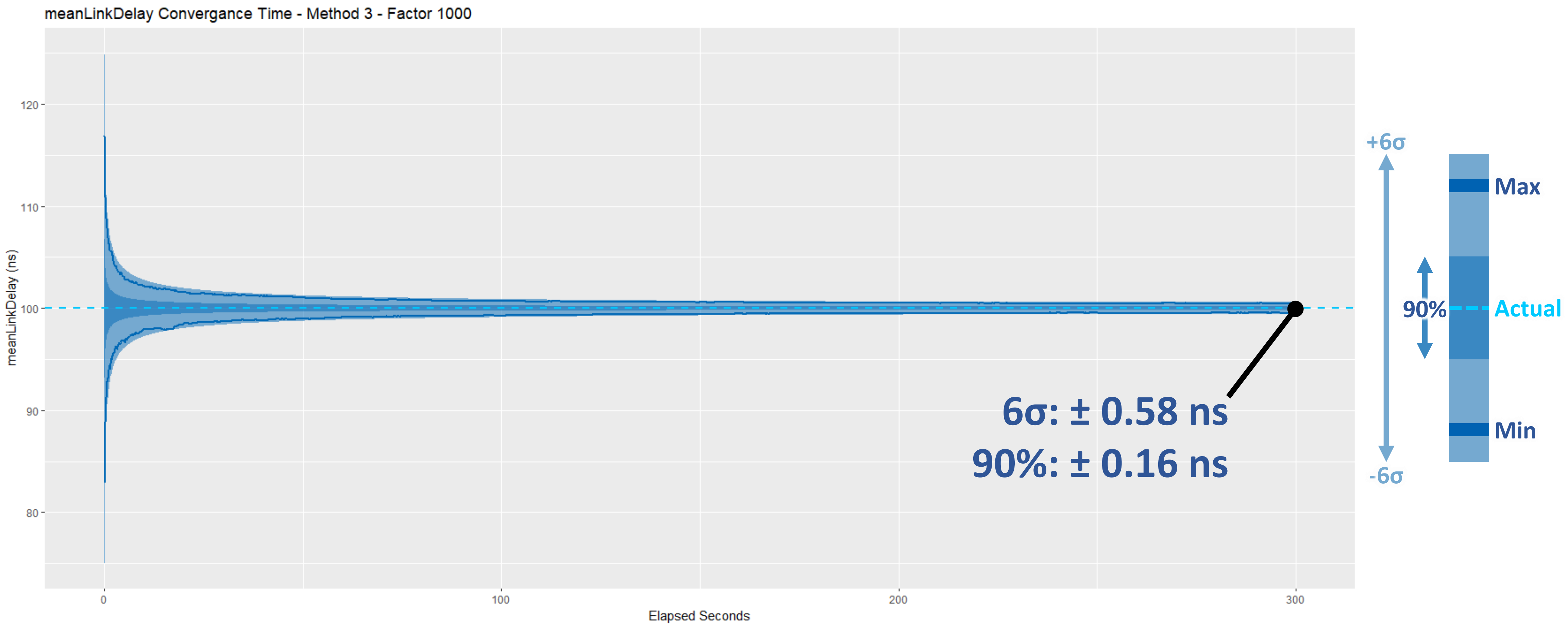




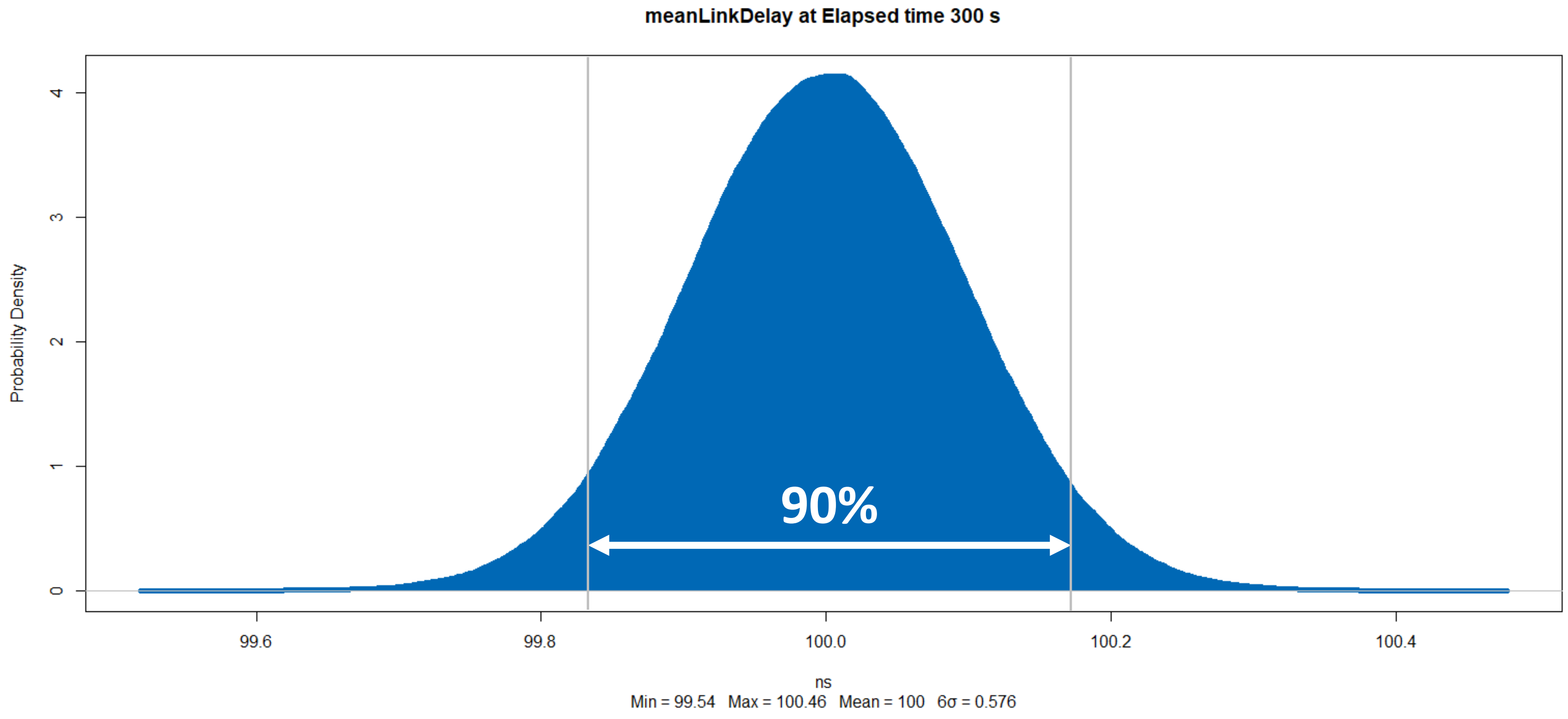




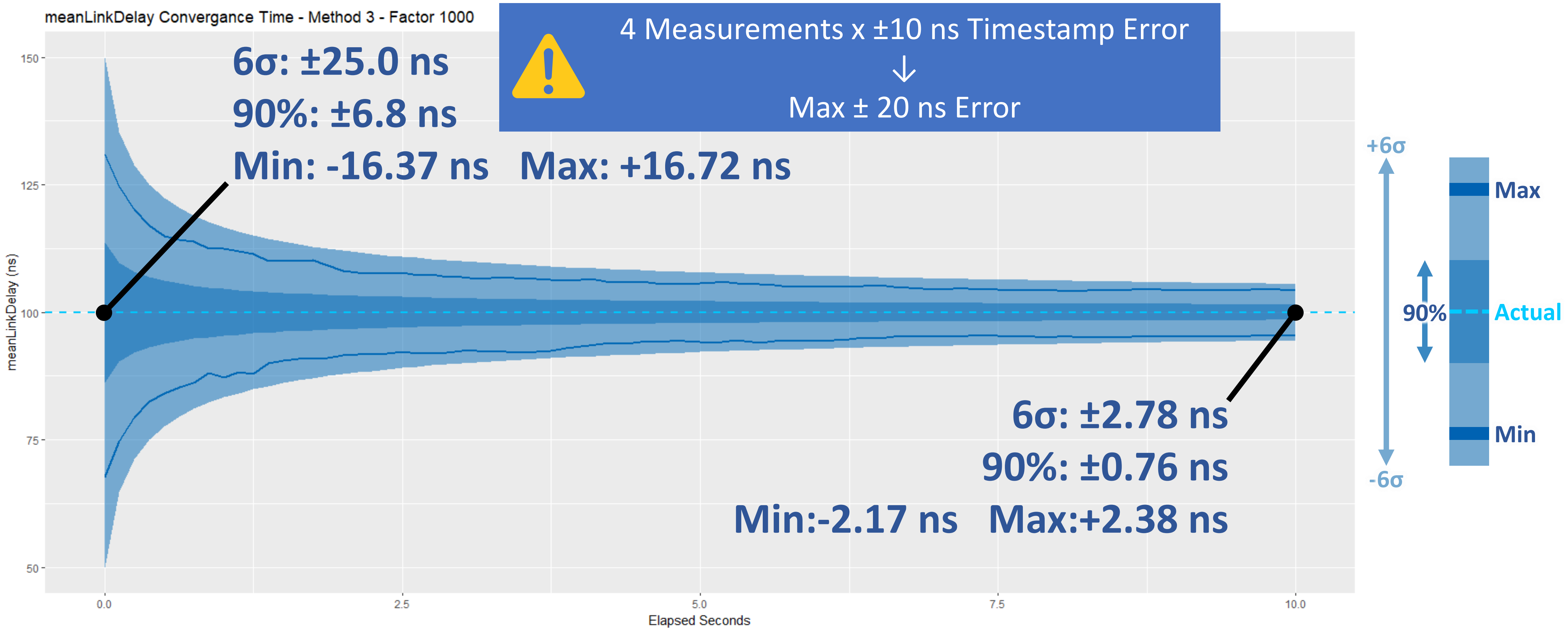
Multiple Runs – 5 mins



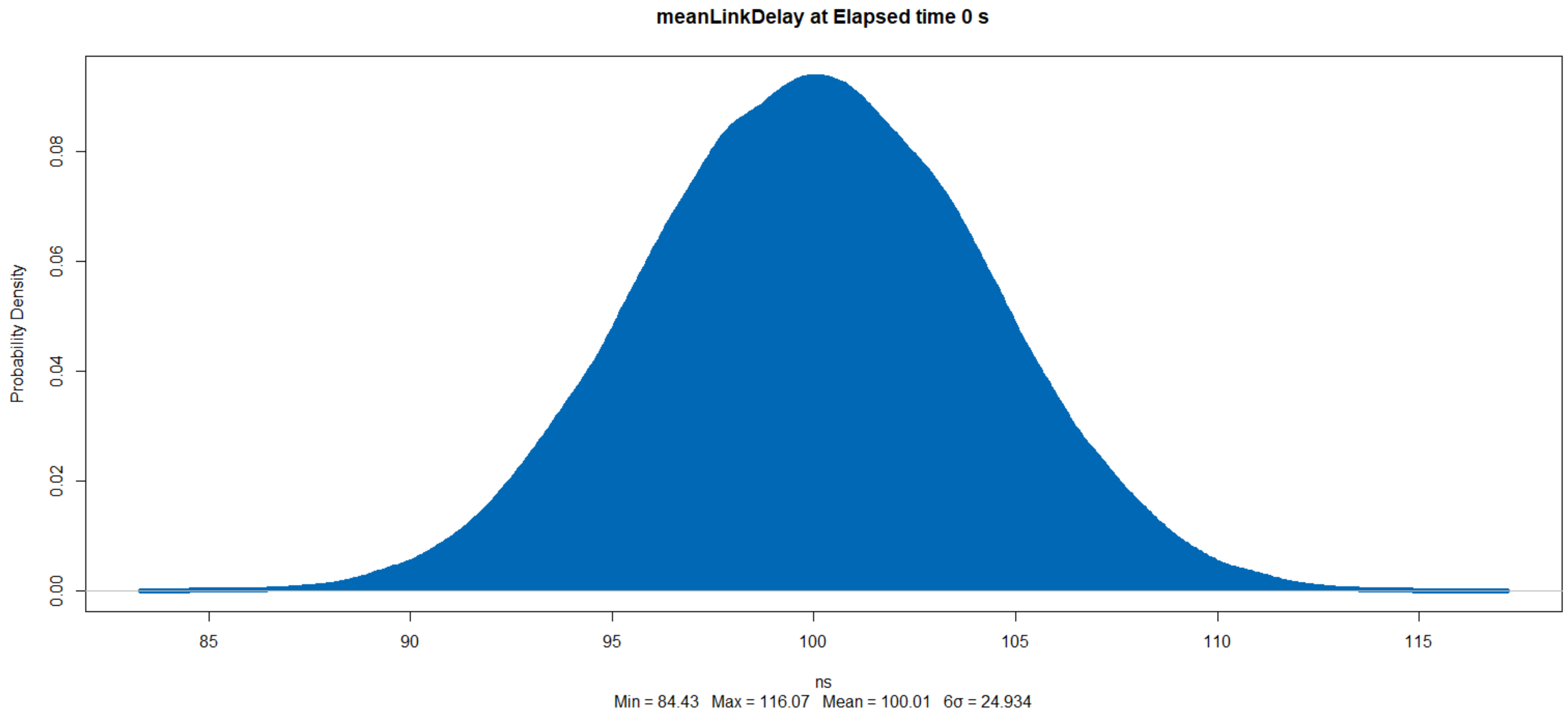
Multiple Runs – Distribution at 5 mins



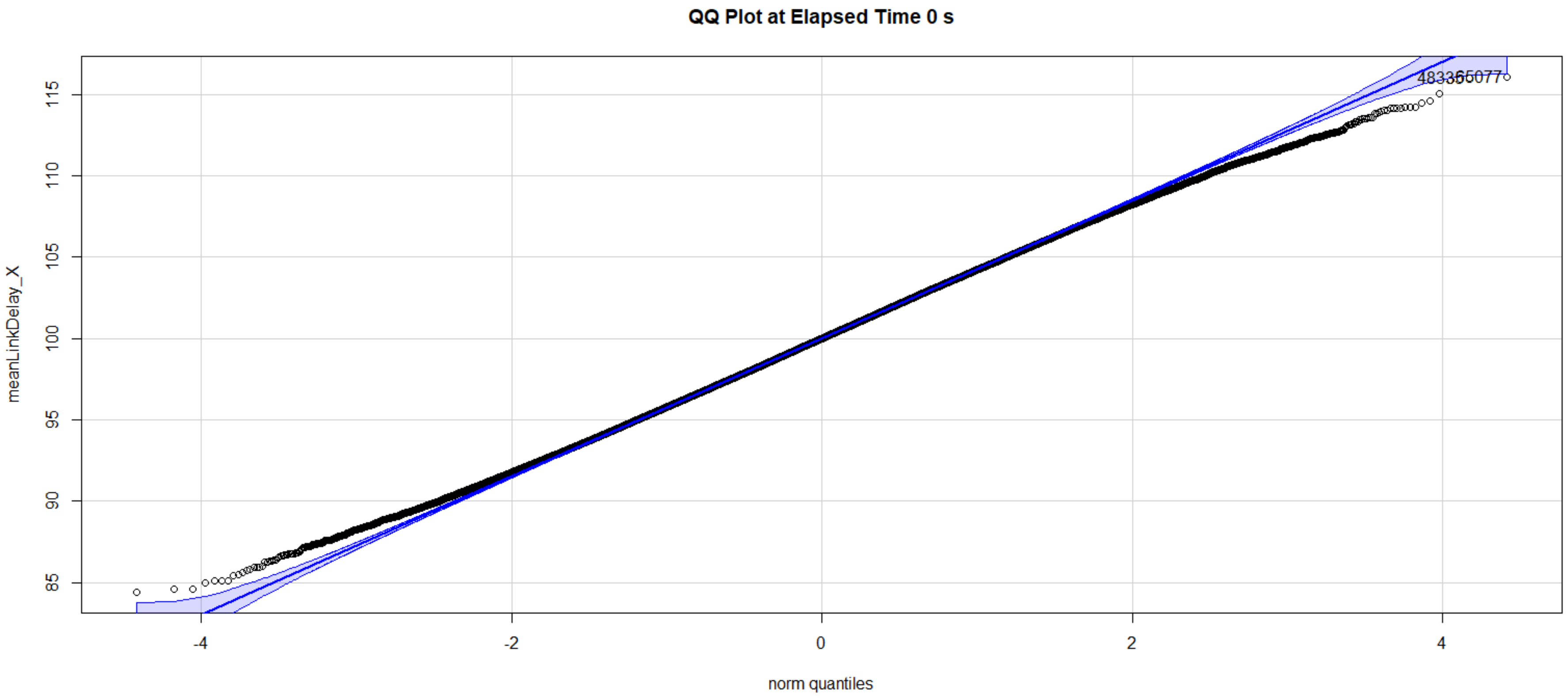
Multiple Runs – First 10 s



Multiple Runs – Distribution at 0 s

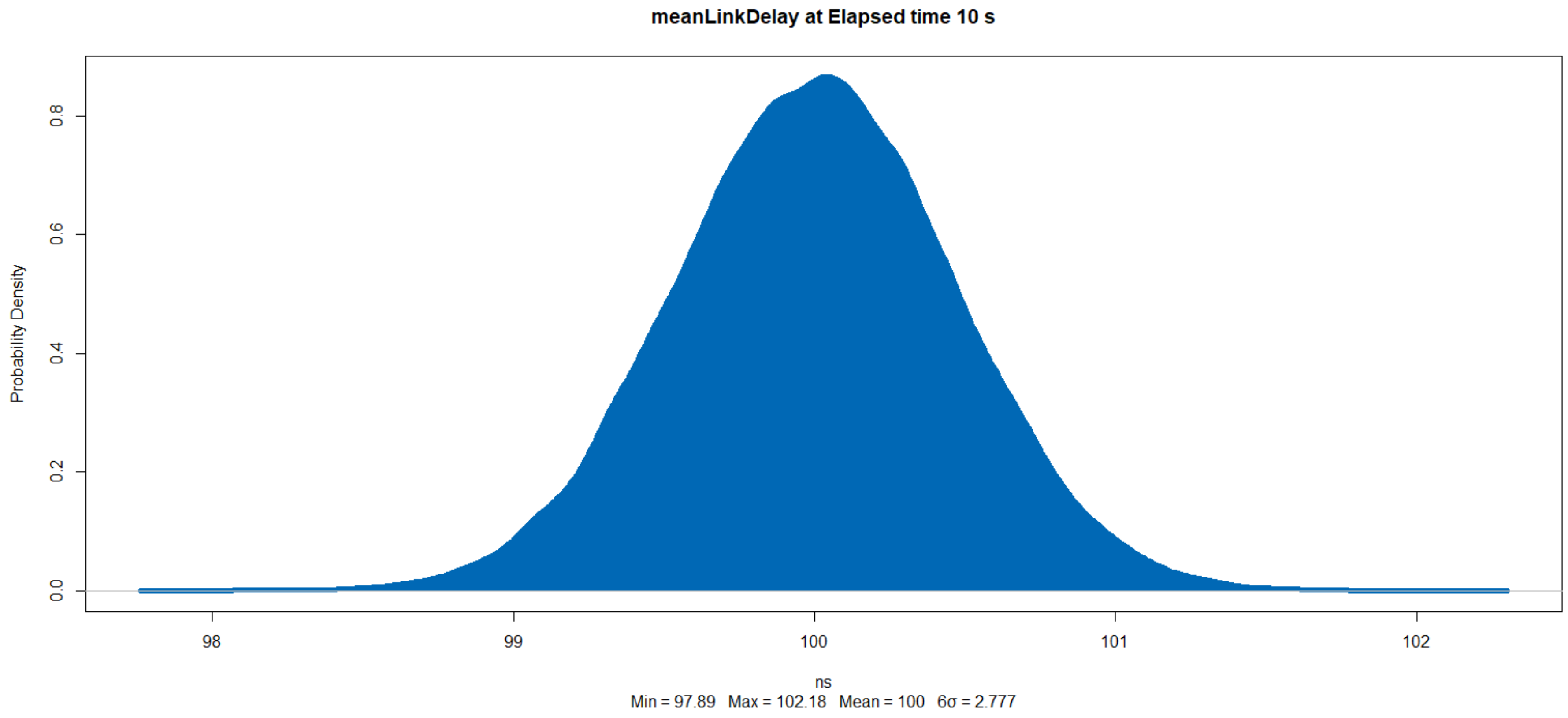


Multiple Runs – QQ Plot at 0s

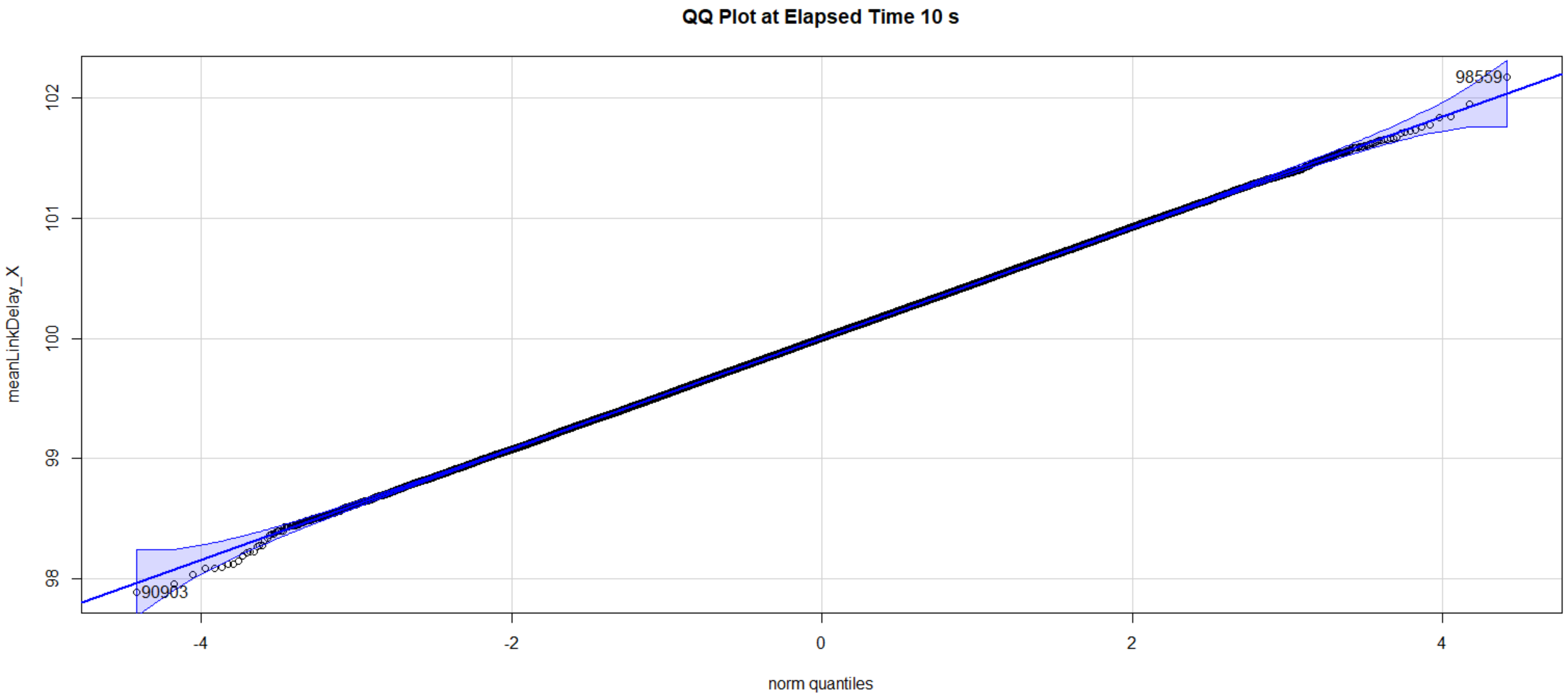


Distribution **can not** be regarded as Gaussian/Normal at 0 s

Multiple Runs – Distribution at 10 s

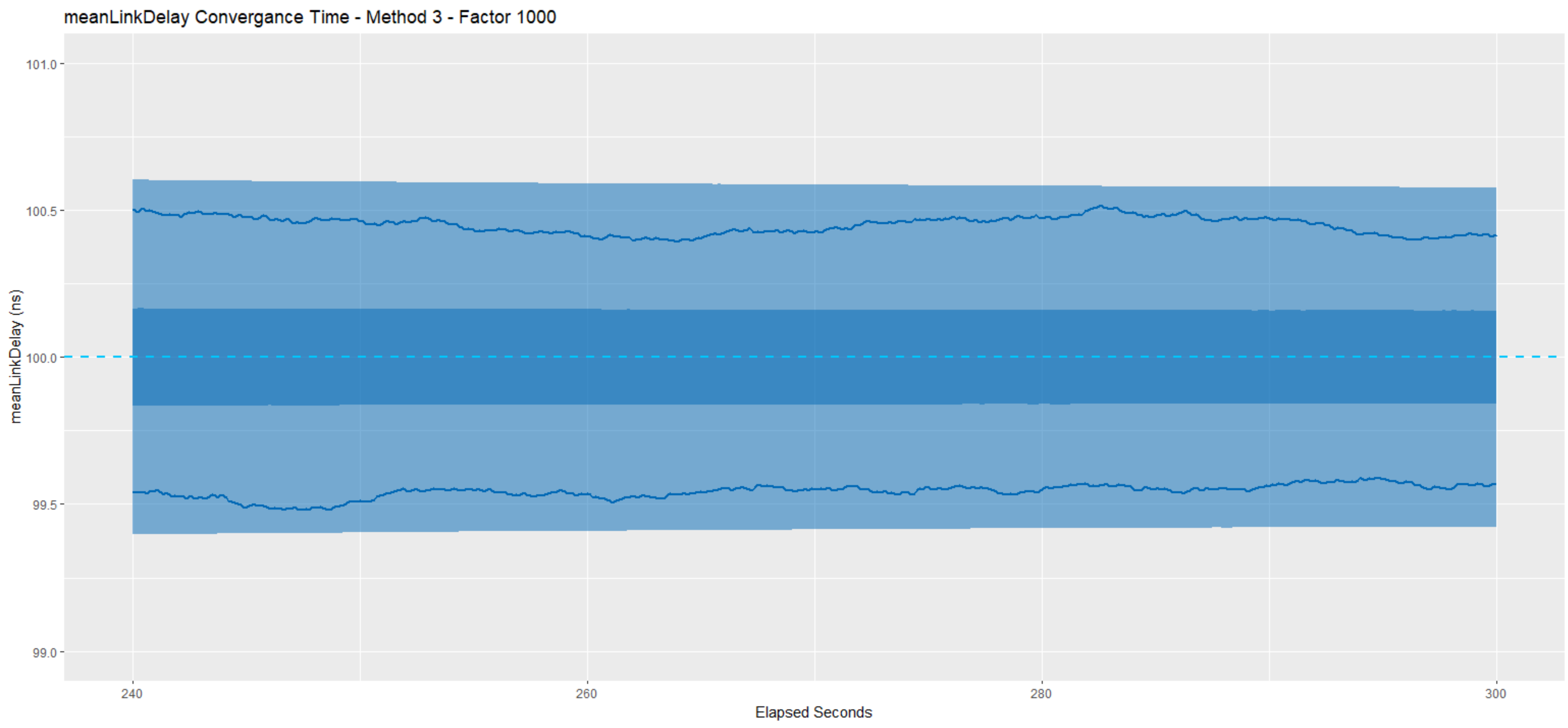


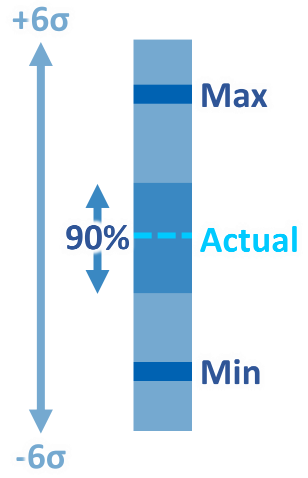
Multiple Runs – QQ Plot at 10s



Distribution **can** be regarded as Gaussian/Normal at 10 s

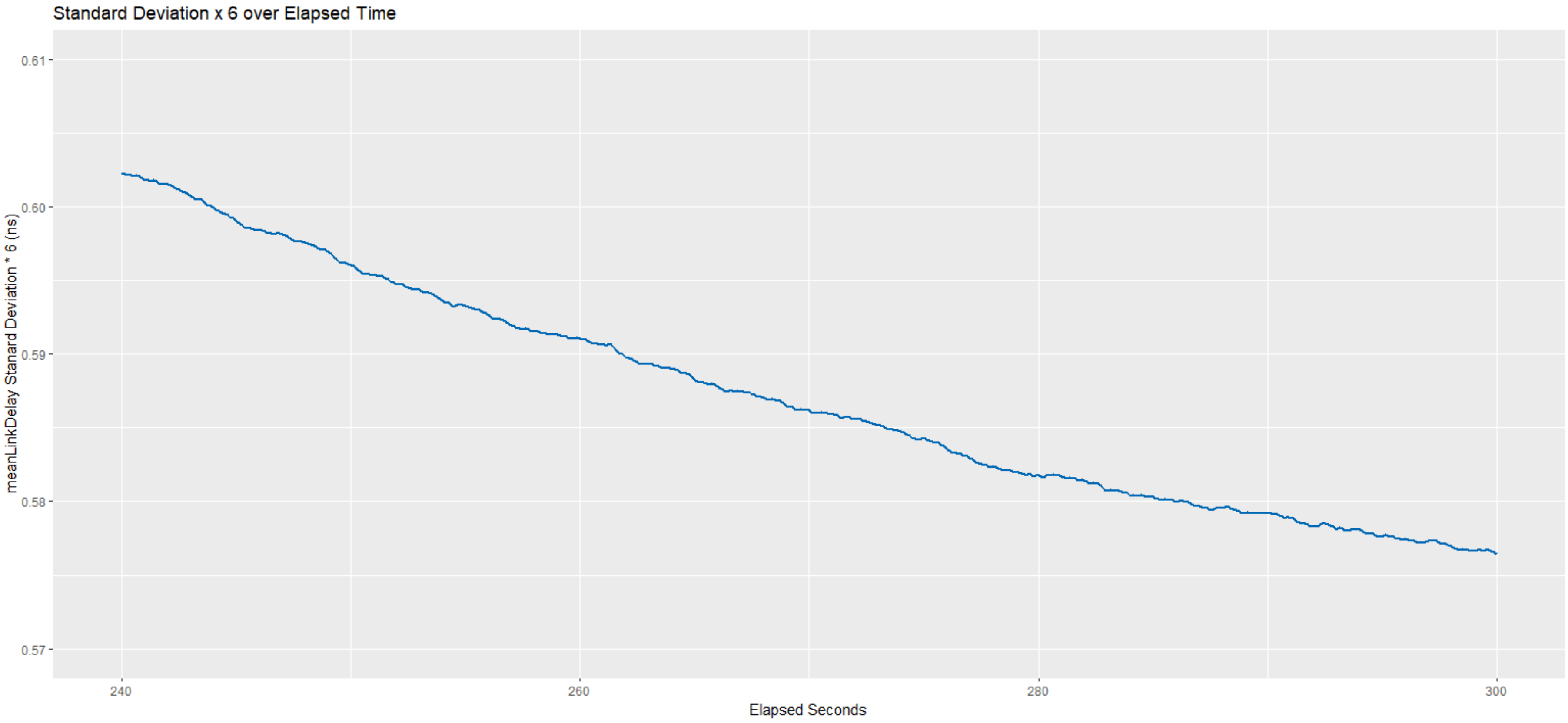
Multiple Runs – 5th Minute





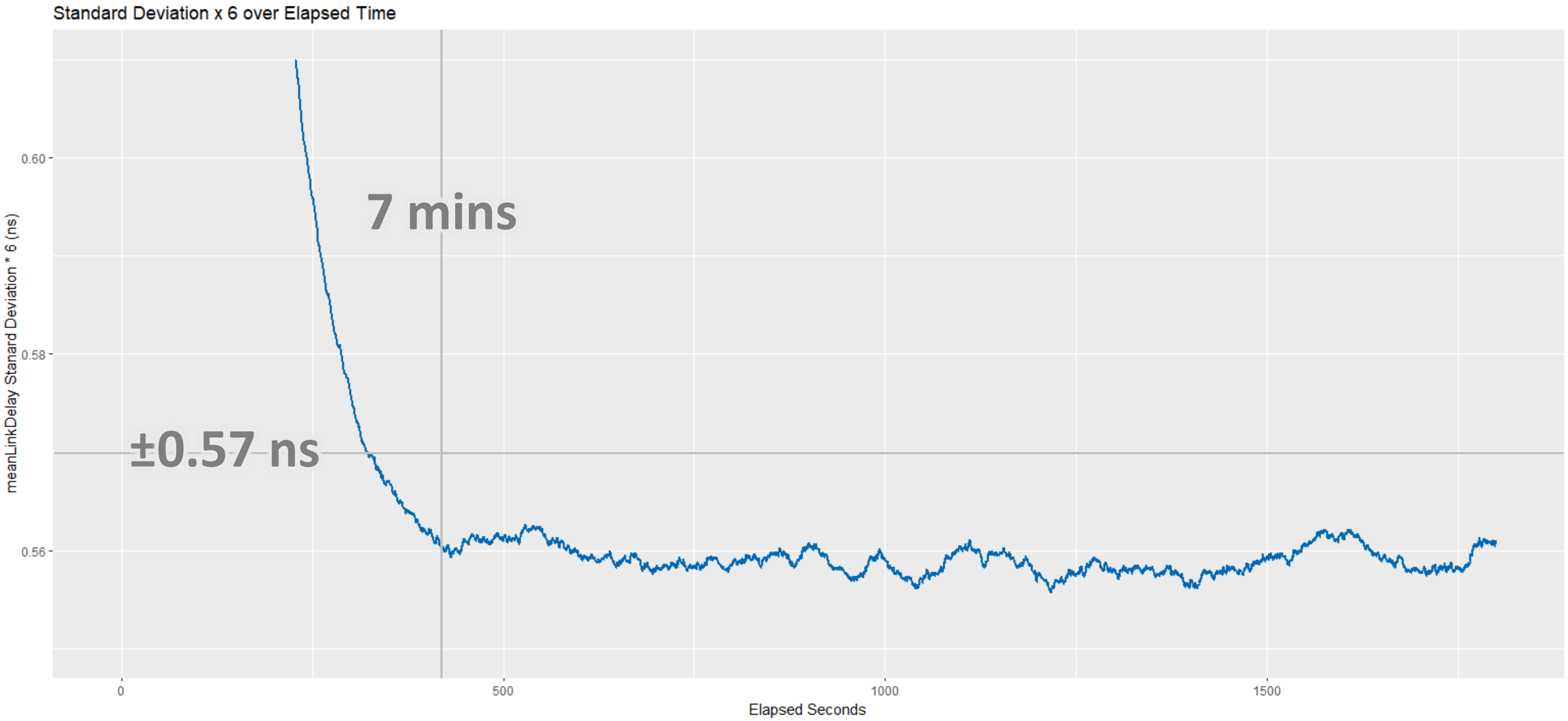
±6σ range is still narrowing after 5 mins

Multiple Runs – 5th Minute



±6σ range is still narrowing after 5 mins

Multiple Runs – 30 mins



±6σ range is stable – within ±0.57 ns – after **7 mins**!

Recommended Algorithm – Startup Behaviour

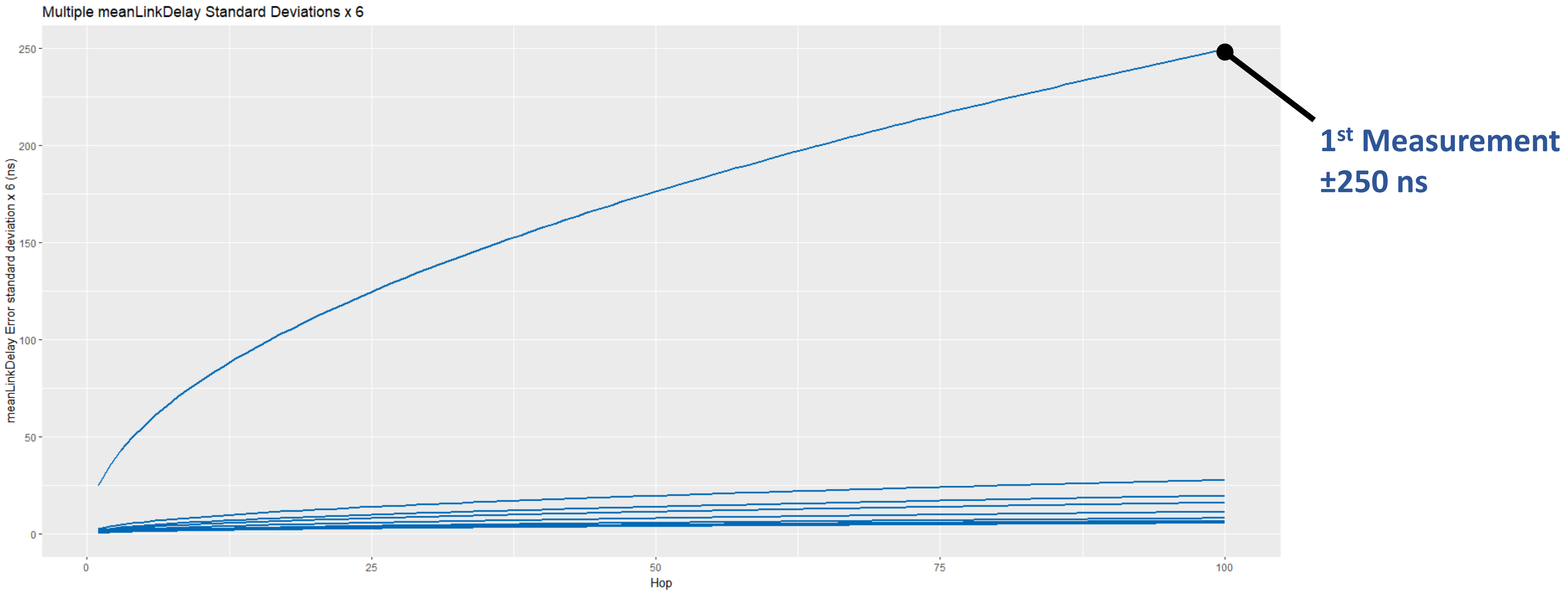
After…	6σ Range (ns)	Notes
1 Measurement	N/A [Feasible Limit ± 20ns]	Distribution can't be treated as Gaussian / Normal. Simulate via TSGE & DTSE.
10 s	±2.78	
20 s	±1.97	
30 s	±1.61	
1 min	±1.14	
2 min	±0.81	
3 min	±0.67	
4 min	±0.60	
5 min	±0.58	
6 min	±0.57	
7 min	±0.56	After 7 mins of simulation 6σ Range varies between ±0.57 ns and ±0.55 ns

Network Level – 100 Hops

- New Monte Carlo Simulation!
  - Assumes normal distribution for meanLinkDelay error
  - Uses data from Multiple Run MLD simulation to determine standard deviation for normal distribution
    - Apart from simulation of 1st measurement, which models each timestamp error (since the distribution at this stage can't be regarded as Gaussian/Normal)
  - Each run simulates a 100-hop network with meanLinkDelay error accumulating down the chain
  - 1 Million Runs x 11 (plus some 100,000 Runs for QQ Plots)
  - Generates probability distribution plots for accumulated meanLinkDelay error at 64 and 100 hops

MLD Error 6σ Range Over 100 Hops

Recommended Algorithm



If there is no averaging, MLD error consumes entire PTP Instance networking-level dTE budget.

60802 Time Error Budget – 1,000 ns

Network Aspect	Error Type	Network Level Error Budget (ns)
All PTP Instances	Constant Time Error	200
	Dynamic Time Error	**600**
All PTP Links	Constant Time Error	200
	Dynamic Time Error	

- 50 ns at Grandmaster and End Instance for dTE between network and application level (50 ns each)
- 600 ns PTP Instance dTE budget – 100 ns = 500 ns
- Without averaging, error in meanLinkDelay can account for half the network-level dTE budget.

Is 6σ the Correct Range?

- If 6σ is the right range to consider for constant steady state operation over a number of years…
  - 1 MLD error outside the range every couple of years
  - (but unlikely to occur at the same time as a similarly large error in the same direction of other contributors towards dTE…and likely to be mitigated by endpoint filtering…i.e. you can't simply add together 6σ values)
- Might a narrower range be a better measure for startup behaviour?
  - If a network starts up once per day and takes 7 mins to fully settle, 6σ range means 1 MLD error outside the range, during startup, on average every 200 years.

Reasons to Stick with 6σ Range

- We're interested in how long the MLD averaging algorithm takes to reach steady state performance, where the 6σ range is appropriate.
- Other errors are considered in terms of 6σ range.
- A lot depends on how often the network is initialised.
- The 6σ range is constantly shrinking throughout the startup period until steady state behaviour is achieved. Difficult to model accurately.
- 6σ range is good enough to indicate algorithm behaviour and error contribution relative to other factors.

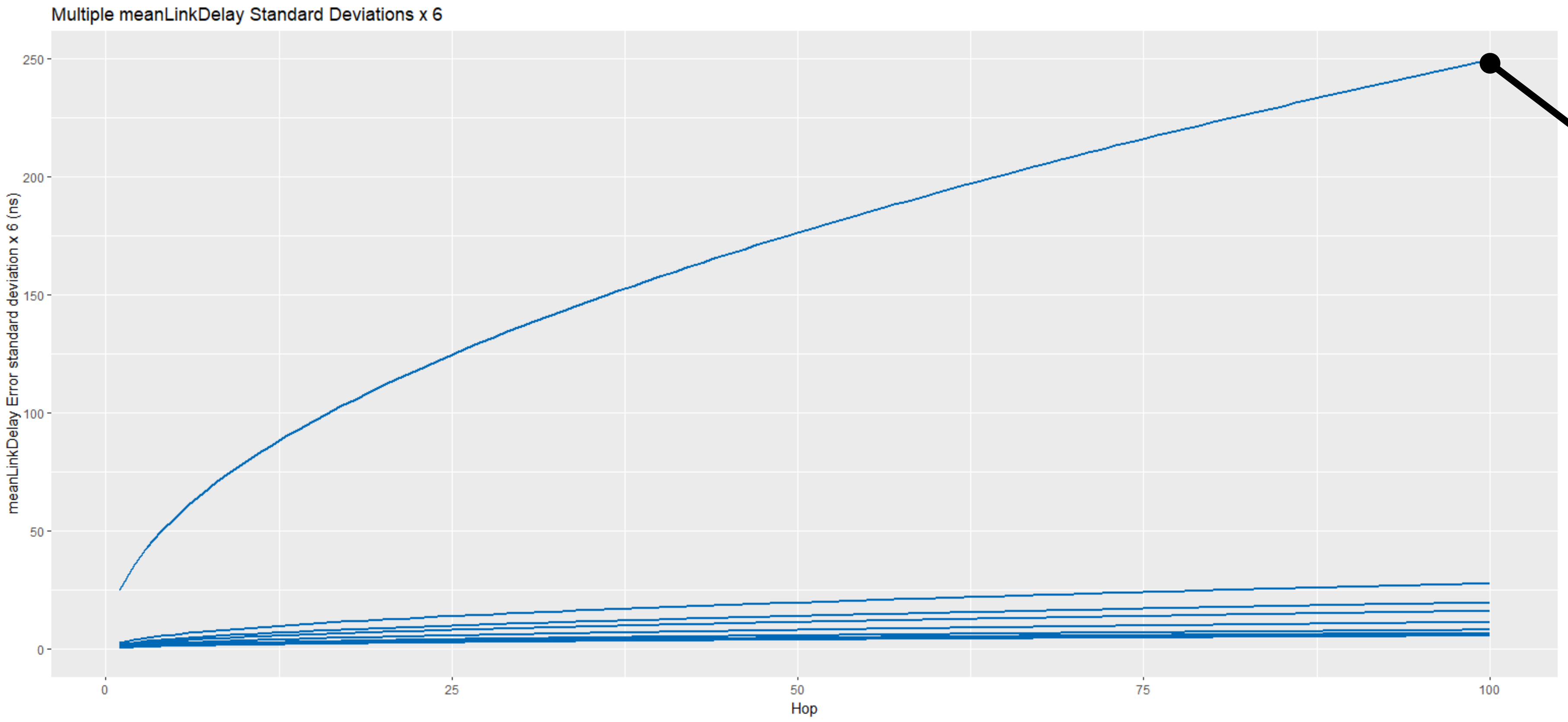
So..sticking with 6σ range.

Meaning of 6σ Range

- When considering startup behaviour, this is the 6σ range value that is useful for considering over the long term operation of the network.
  - It is **not** as directly useful for considering the likelihood of an out-of-range error during the startup period.
  - But it's still useful for considering and comparing startup behaviours and the magnitude of errors that are likely to be seen.

MLD Error 6σ Range Over 100 Hops

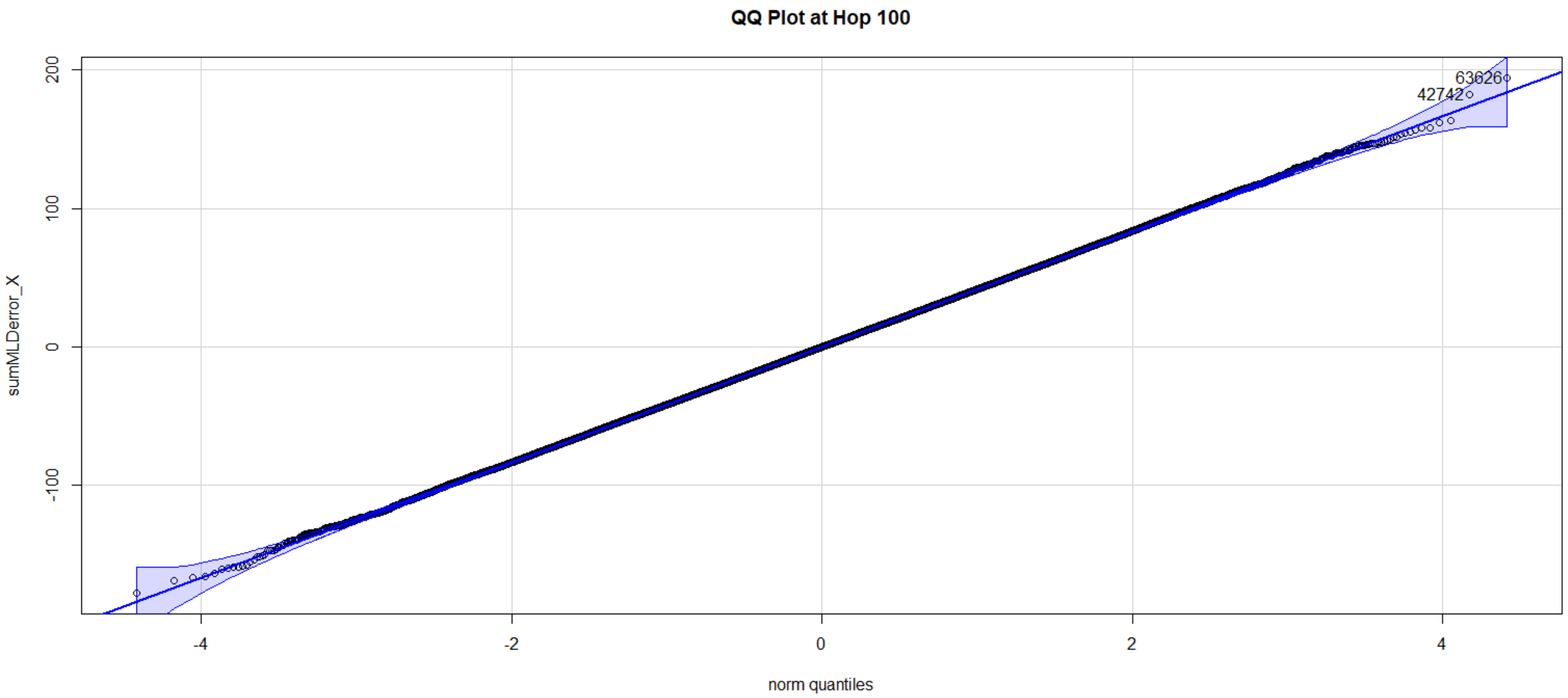
Recommended Algorithm



1st Measurement ±250 ns

"1st Measurement" indicates a likely worst case error if no algorithm is employed.

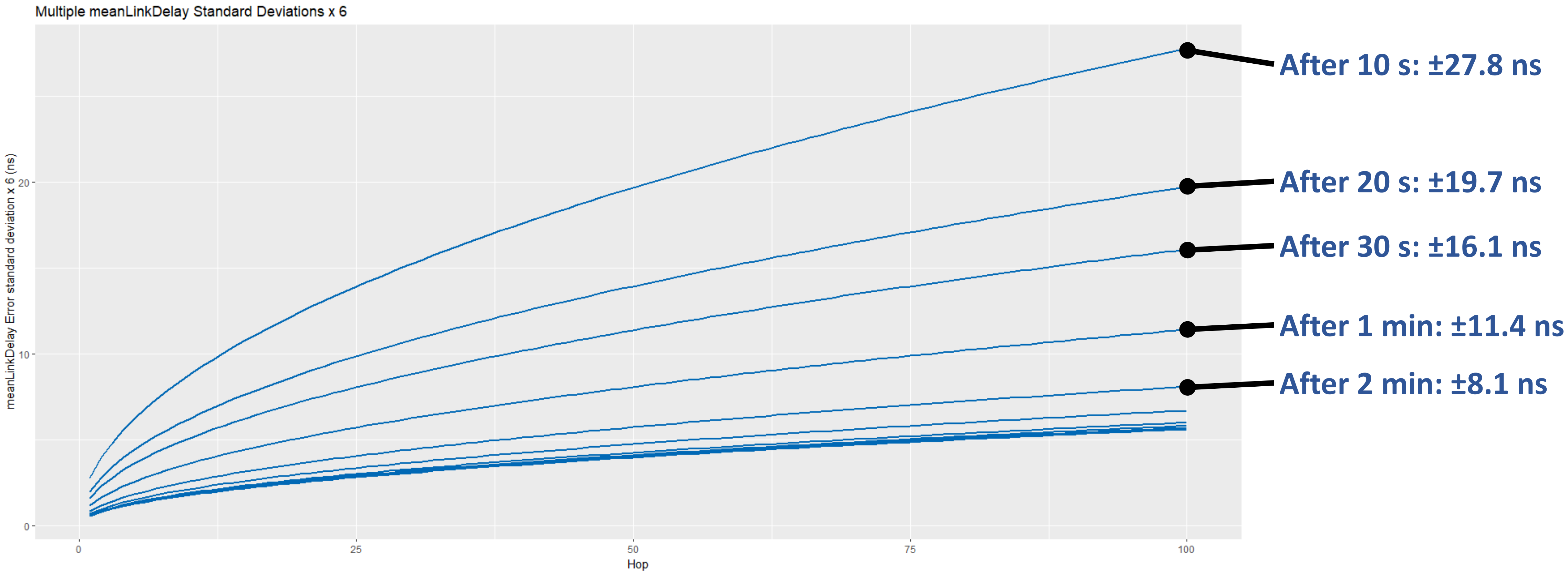
MLD Error 6σ Range without Algorithm at Hop 100 - QQ Plot



Distribution at 1st hop **can not** be regarded as Gaussian. Distribution at 100th hop **can**.

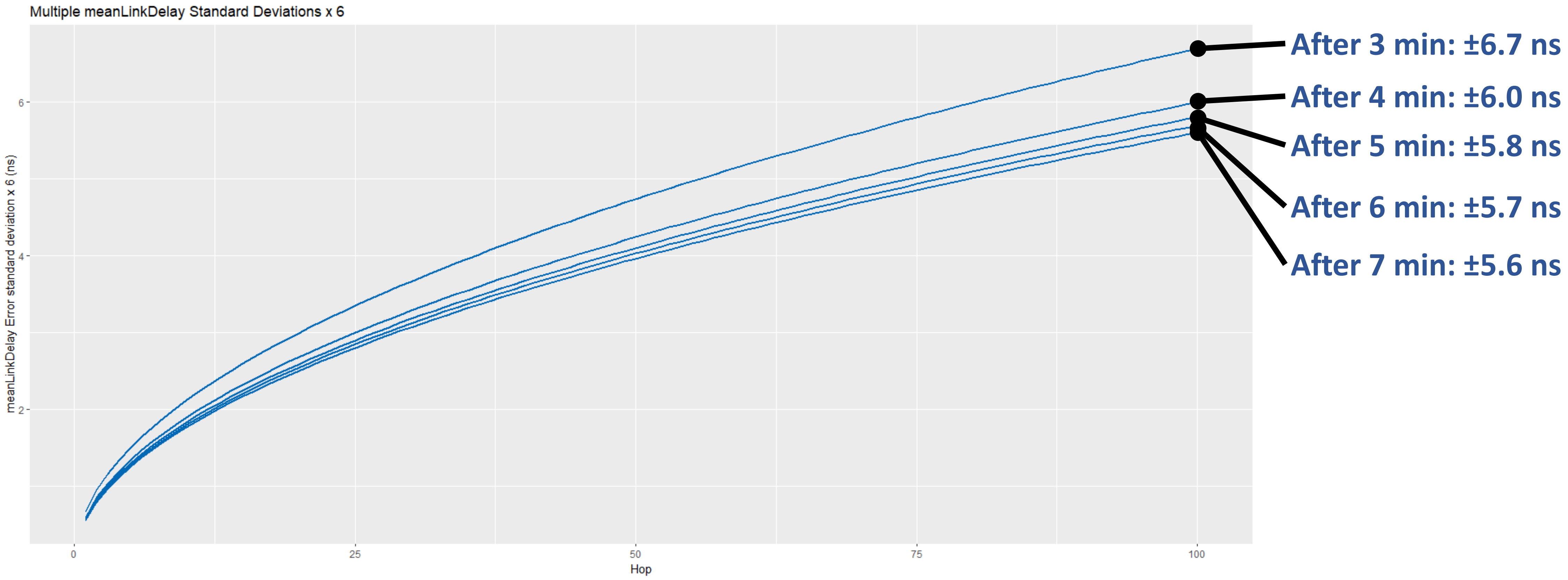
MLD Error 6σ Range Over 100 Hops

Recommended Algorithm



MLD Error 6σ Range Over 100 Hops

Recommended Algorithm



6σ Range After 1 Hop vs After 100 Hops

After…	At 1st Hop 6σ Range (ns)	At 100th Hop 6σ Range (ns)
1 Measurement	N/A [Feasible Limit ±20ns]	±250
10 s	±2.78	±27.8
20 s	±1.97	±19.7
30 s	±1.61	±16.1
1 min	±1.14	±11.4
2 min	±0.81	±8.1
3 min	±0.67	±6.7
4 min	±0.60	±6.0
5 min	±0.58	±5.8
6 min	±0.57	±5.7
7 min	±0.56	±5.6

x 10

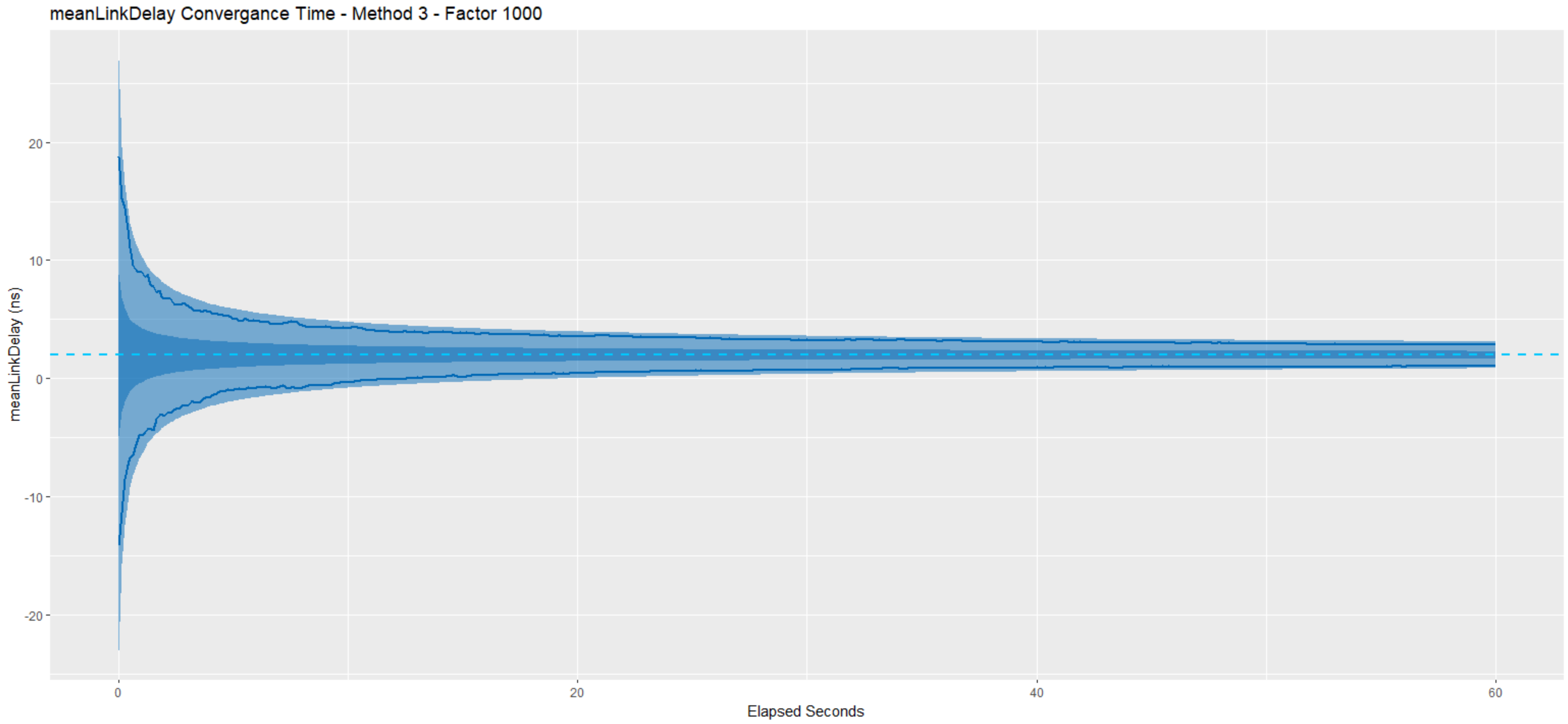
Rule of Thumb

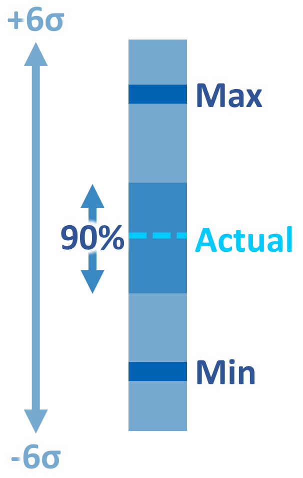
Don’t Truncate to 0 ns Link Delay!

- Truncating to 0 ns (results that are less than 0 ns are replaced with 0 ns) might seem intuitive (zero or negative link delay is impossible absent time travel) but it causes problems.
- There are two possibilities…
    - Truncate each Path Delay measurement to zero, prior to the IIR filter.
        - Simulated on following two slides
    - Truncate the meanLinkDelay to zero, if the output of the IIR filter is less than zero.
        - Not simulated. Effect will be to average time to full accuracy of meanLinkDelay.

Link Delay 2 ns – 1 Hop

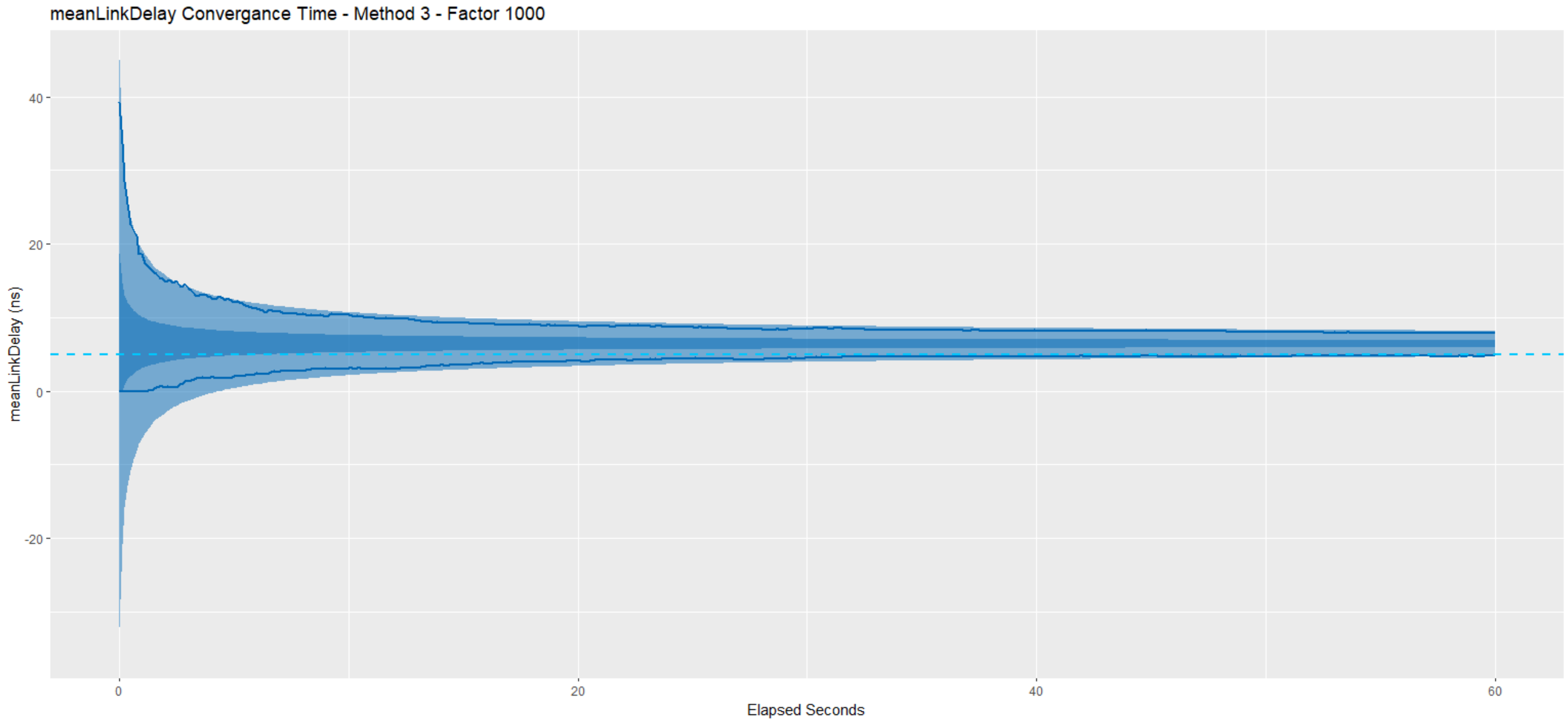
Without Truncating of Path Delay Measurement

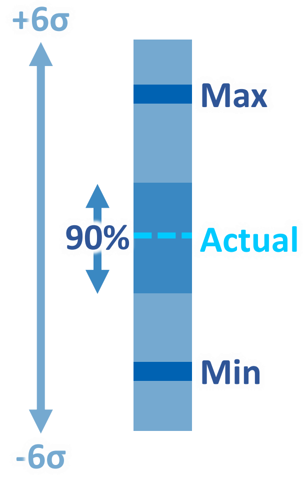




Link Delay 2 ns – 1 Hop

With Truncation of Path Delay Measurement





In this example, mean of meanLinkDelay stabalises at 2.86 ns.

Ramping the Filter Factor is Valuable

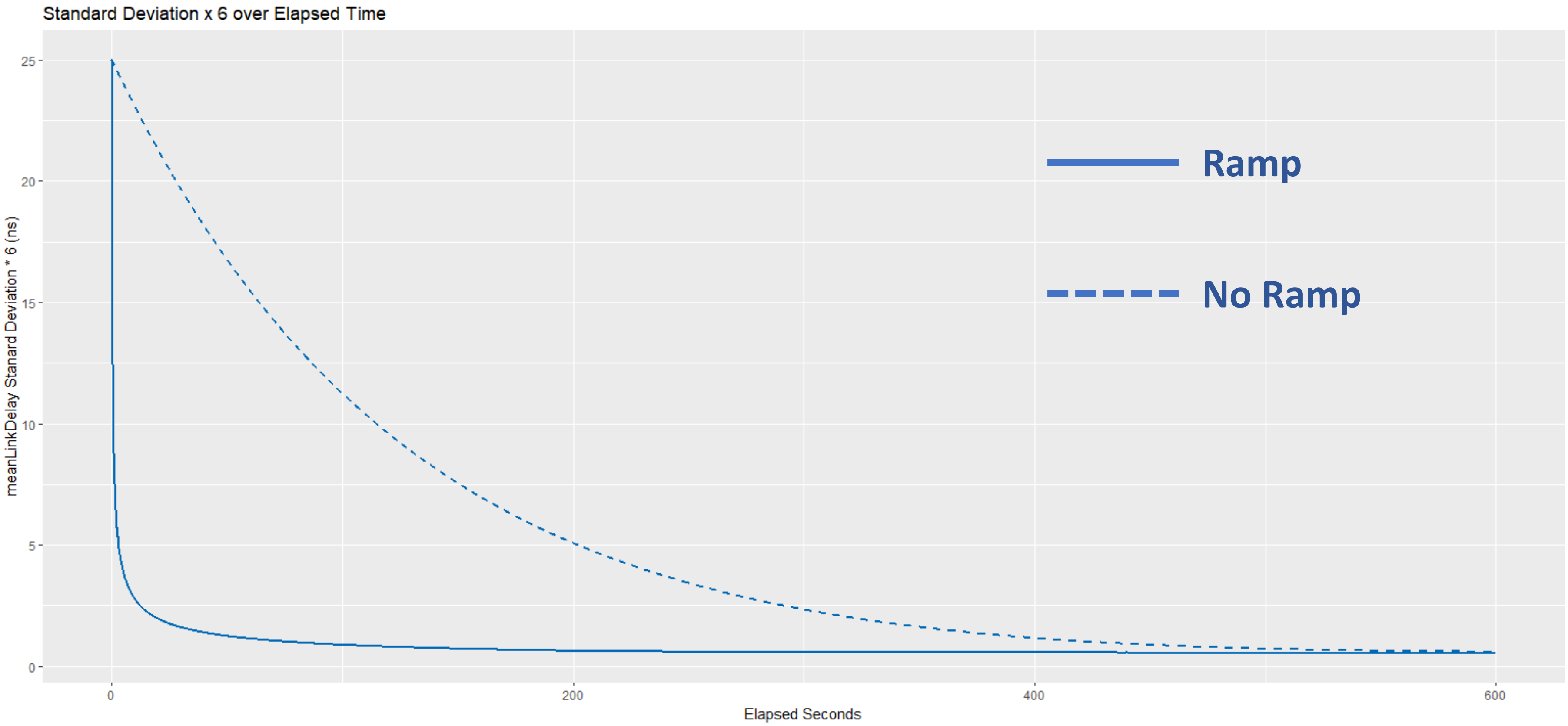
- There is a big difference between ramping the filter factor…

$$\text{If } x < 1000 \text{ then } \alpha = \frac{1}{x} \text{ else } \alpha = \frac{1}{1000}$$

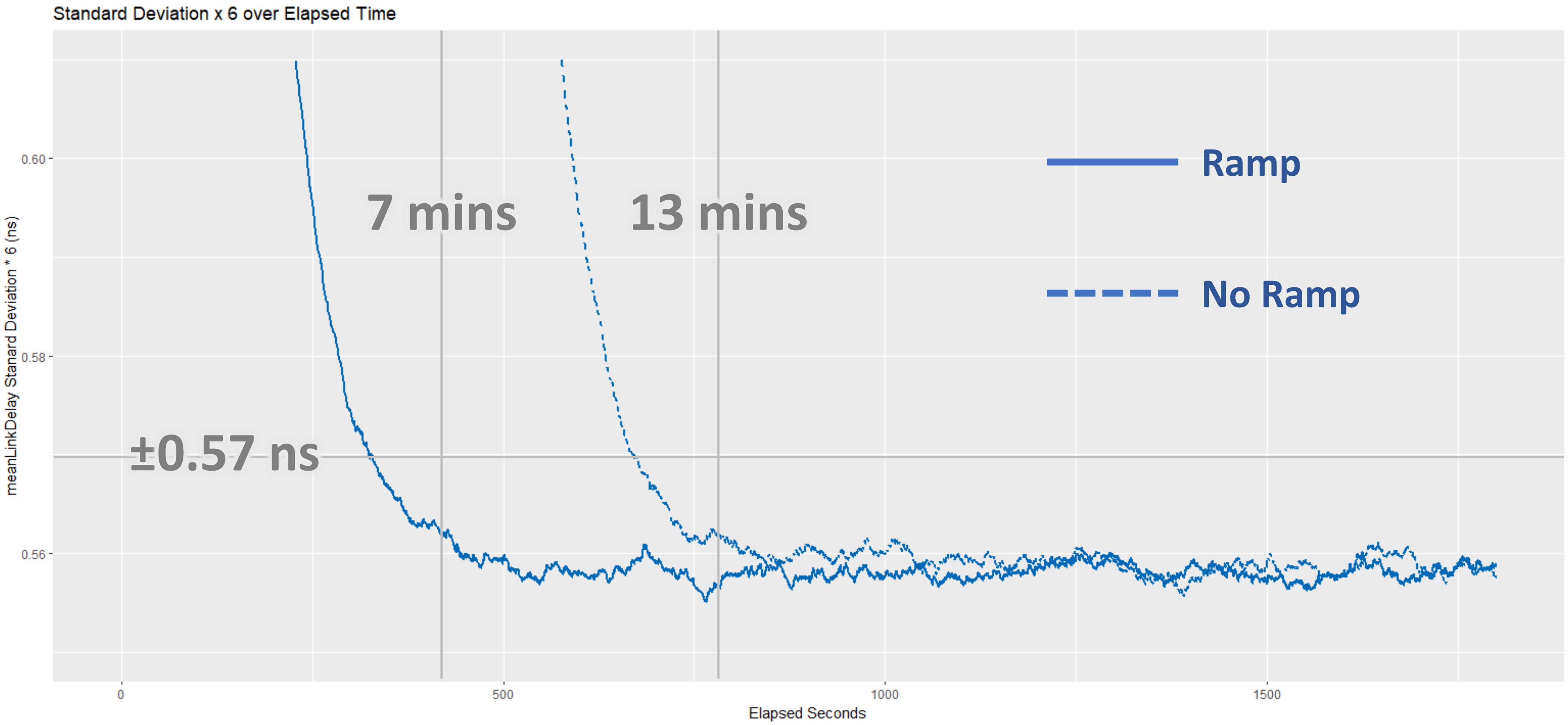
- …verses not ramping…

$$\alpha = \frac{1}{1000}$$

Ramp vs No Ramp



Ramp vs No Ramp



Without Ramping, meanLinkDelay takes 13 mins to settle, vs 7 mins with Ramping

Don’t forget to initialise the filter with the first measurement…

- This…

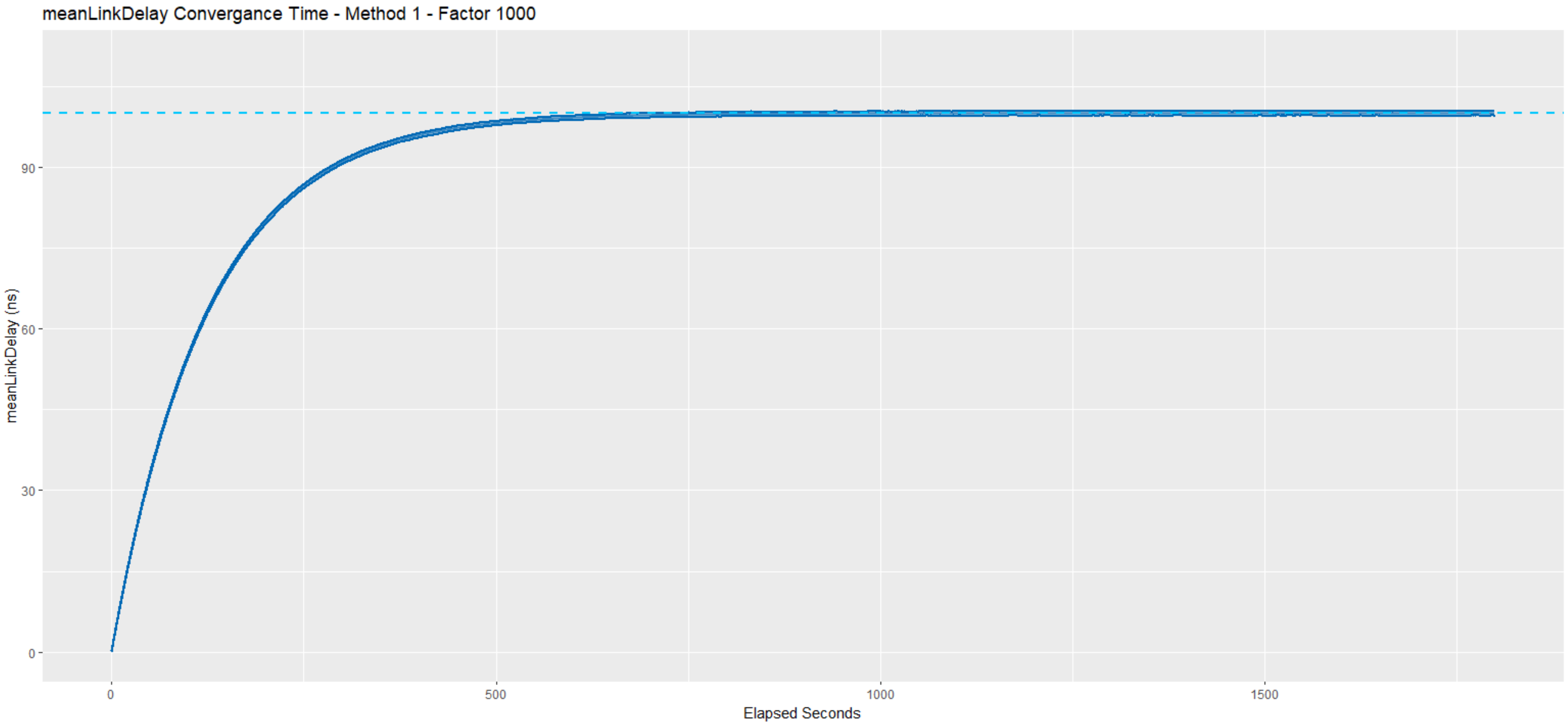
If $x = 1$ $\quad meanLinkDelay(x) = mPathDelay(x)$

- …is very different from this…

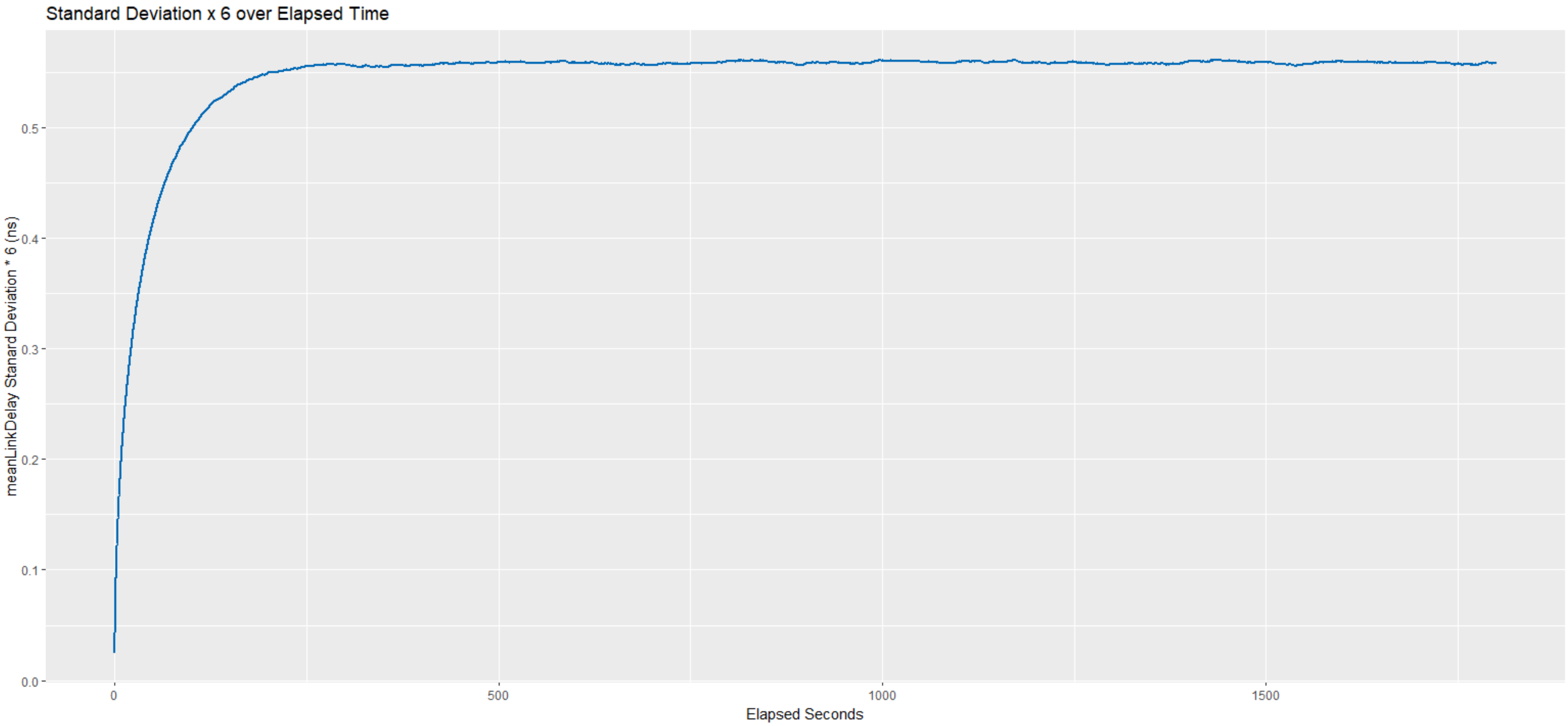
If $x = 1$ $\quad meanLinkDelay(x) = 0 + \alpha \times mPathDelay(x)$

- …which also implies no ramping of the filter factor.

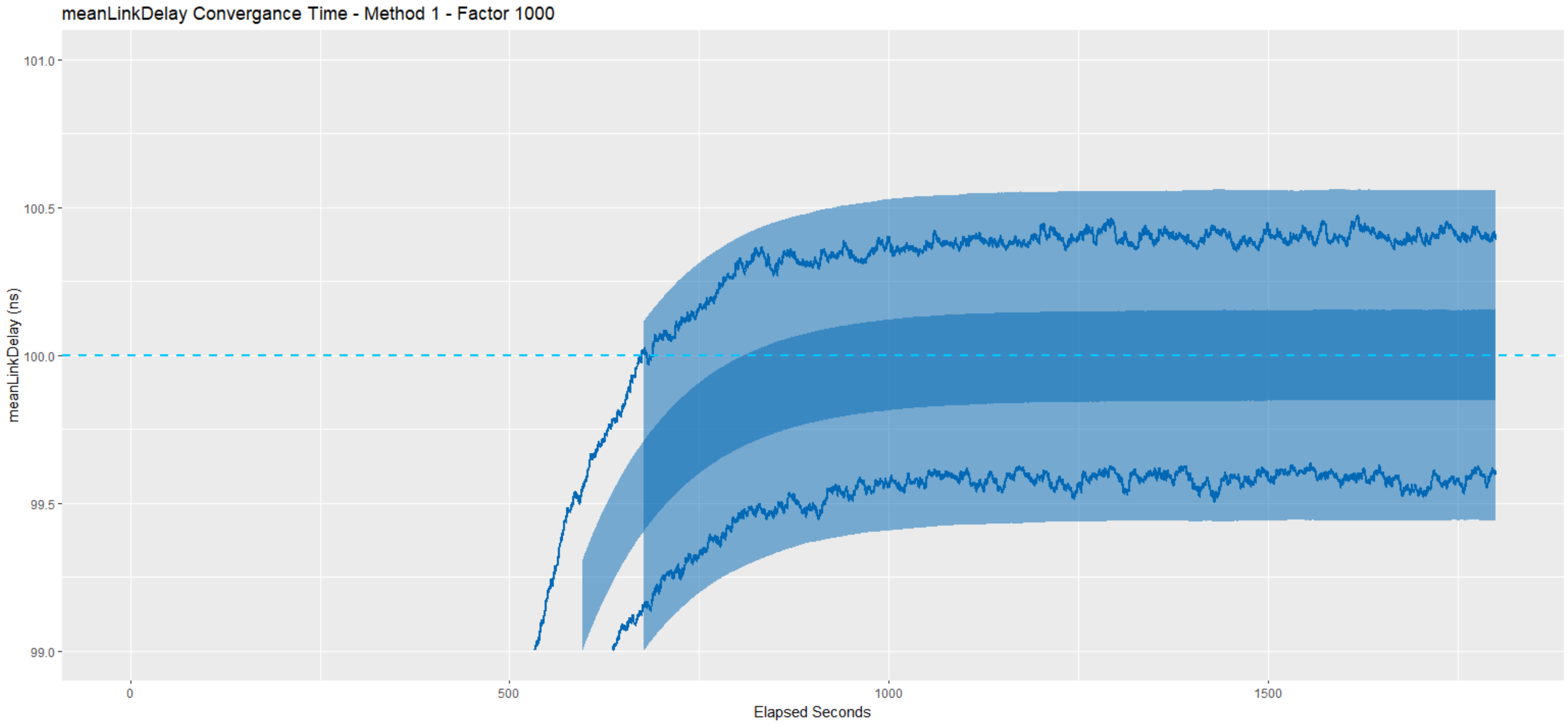
MLD Error With Incorrect Initialisation

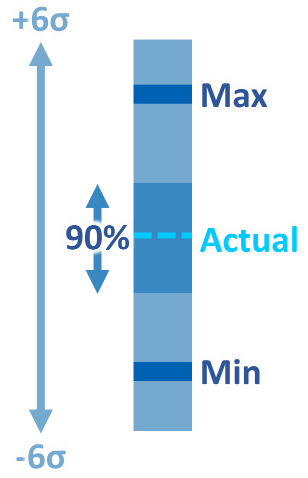


MLD Error With Incorrect Initialisation



MLD Error With Incorrect Initialisation





Without correct initialisation (and without ramping) meanLinkDelay error can take 20 mins to stabalise

Dos & Don’ts Summary

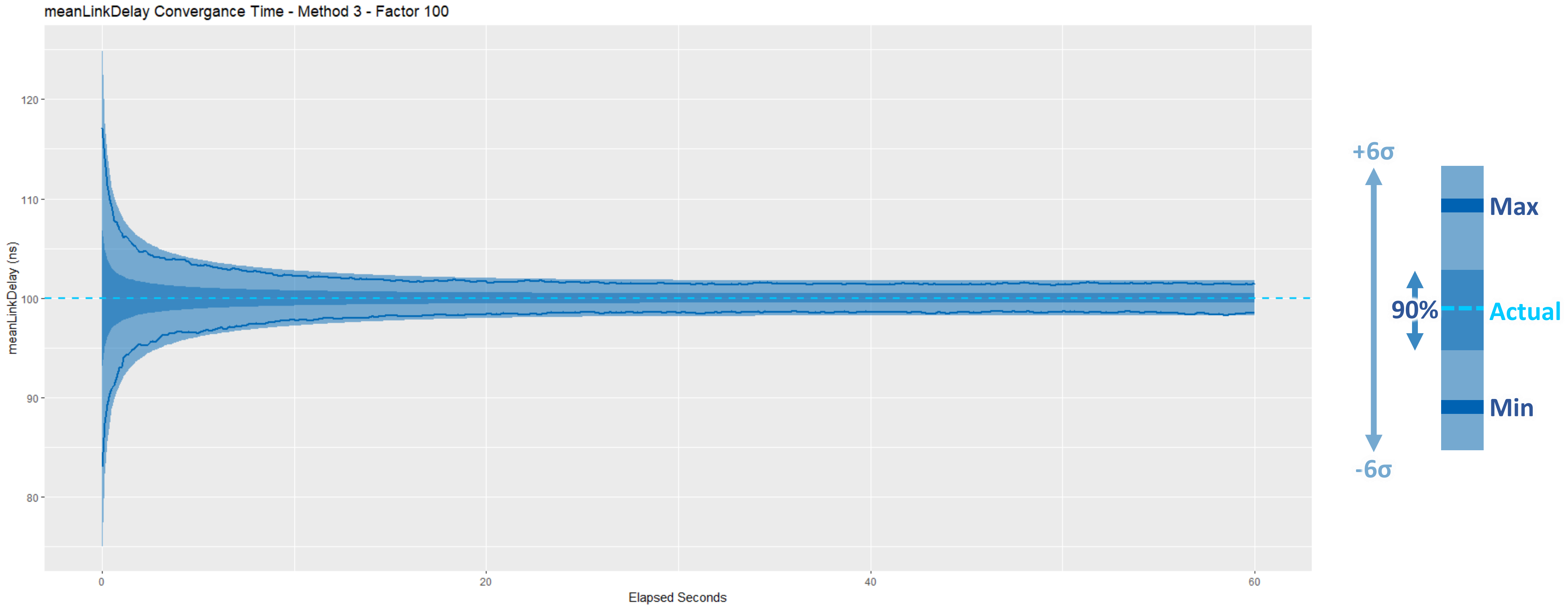
- Do
  - Ramp the IRR filter factor
  - Initialise the filter with the first measurement
- Don’t
  - Truncate path delay measurements or meanLinkDelay to zero

Implications for Simulations

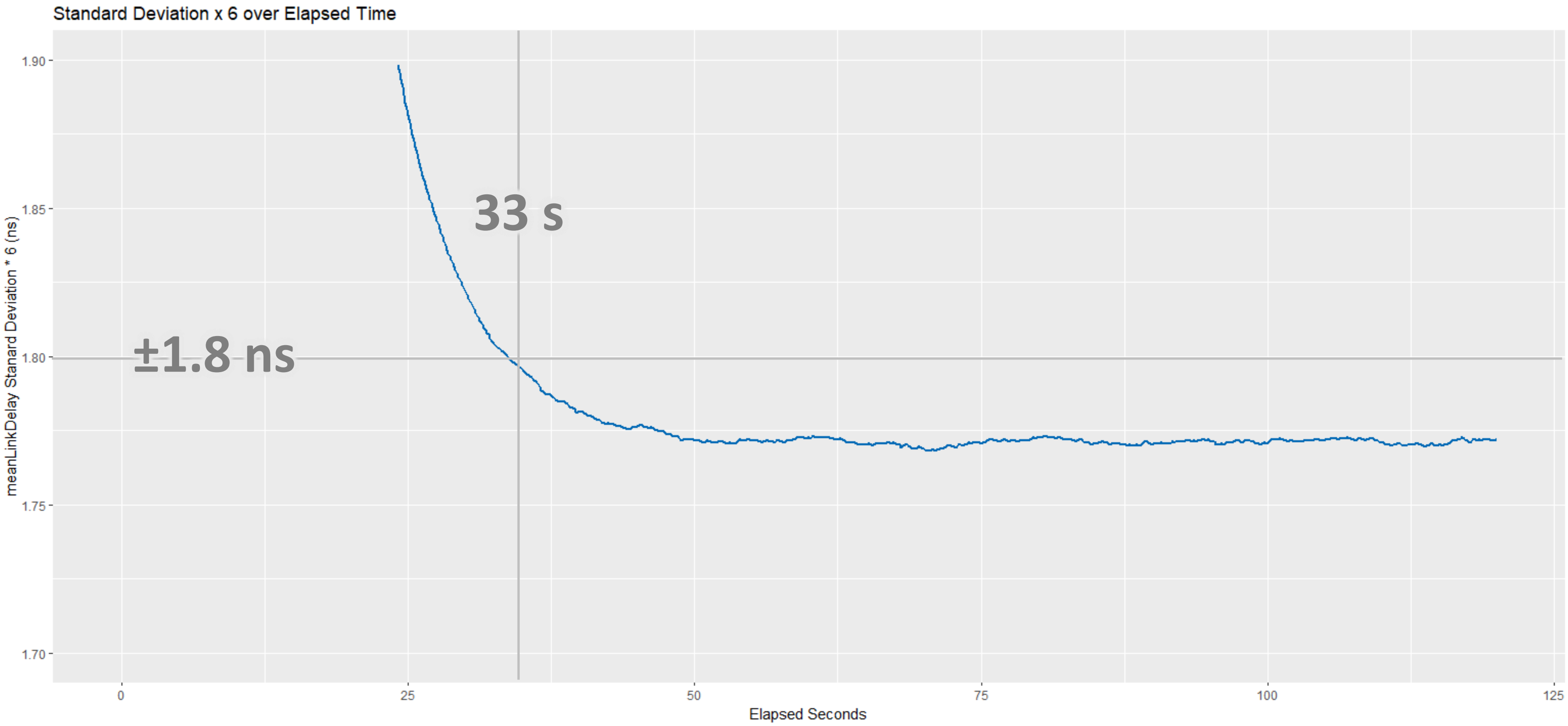
Time Series Simulations

- Recent Time Series simulations used a factor of 100 (not the recommended 1000)
- Time Series simulations also discard the first 50 s of data for the purposes of calculating dTE statistics
  - Simulation time is 3,100 s i.e. 3,050 is used for calculating dTE statistics

MLD Error – Factor of 100



MLD Error – Factor of 100



Factor of 100 settles to ±1.8 ns after 27 s (same ±1.8 ns for factor of 1000 @ 27 s ; but ±0.57 ns after 7 mins)

Time Series Simulations – Implications

- Recent Time Series simulations effectively had MLD distribution with 6σ Range of ±1.8 ns per node; ±18 ns over 100 hops.
- If recommended settings are used, MLD distribution 6σ Range of ±0.57 ns per node; ±5.7 ns over 100 hops…but only after 7 mins
  - If the recommended algorithm is used, the Time Series starts assessing dTE after 50 seconds, when MLD distribution 6σ Range is ±1.25 ns.
- Each replication spends 370 s where MLD distribution 6σ Range after 100 hops is…
  - …between ±6 ns and ±12 s worse than recommended settings for 370 s
  - ±12 ns worse than recommend settings for 2,680 s
- ±12 ns worse is the steady-state behaviour

Time Series Simulations – Recommendations

- For simulations targeting steady-state behaviour
  - Initialise IIR filter for each node with a value from the normal distribution:
    - Mean: actual path delay
    - Standard Deviation: 0.3 ns
  - Valid for TSGE = ±4 ns; DTSE = ±6 ns
  - For other combinations of TSGE and DTSE, matching Monte Carlo simulations can generate the appropriate standard deviation
- For simulations targeting initialisation behaviour, use recommended algorithm

Monte Carlo Simulations

- Initial simulations used a % effective value to emulate an algorithm
  - For a give % effective, that % of the error was eliminated.
  - Simulations typically used a value of 95% effective
  - This contribution illustrates a reduction from MLD Error distribution 6σ Range at 100 hops of ±500 ns to ±11.1 ns, i.e. 97.8% effective.
- Recent simulations took an average of 50 Pdelay calculations, which is the equivalent of the IRR filter after 6.125 s
  - Effective MLD Error distribution 6σ Range at 100 hops of ±70.1 ns
  - This is ±59 ns worse than what the recommended algorithm can achieve at steady state.

Monte Carlo Simulations – Recommendations

- For MLD Error (from Timestamp Error) use a value from the normal distribution:
  - Mean: actual path delay
  - Standard Deviation: 1.88 ns
  - This calculation won’t just be more accurage that previous method (average of 50 path delay calculations), it will be much faster than most recent method
- Valid for TSGE = ±4 ns; DTSE = ±6 ns
- For other combinations of TSGE and DTSE, matching Monte Carlo simulations can generate the appropriate standard deviation

Normative Requirements

Background

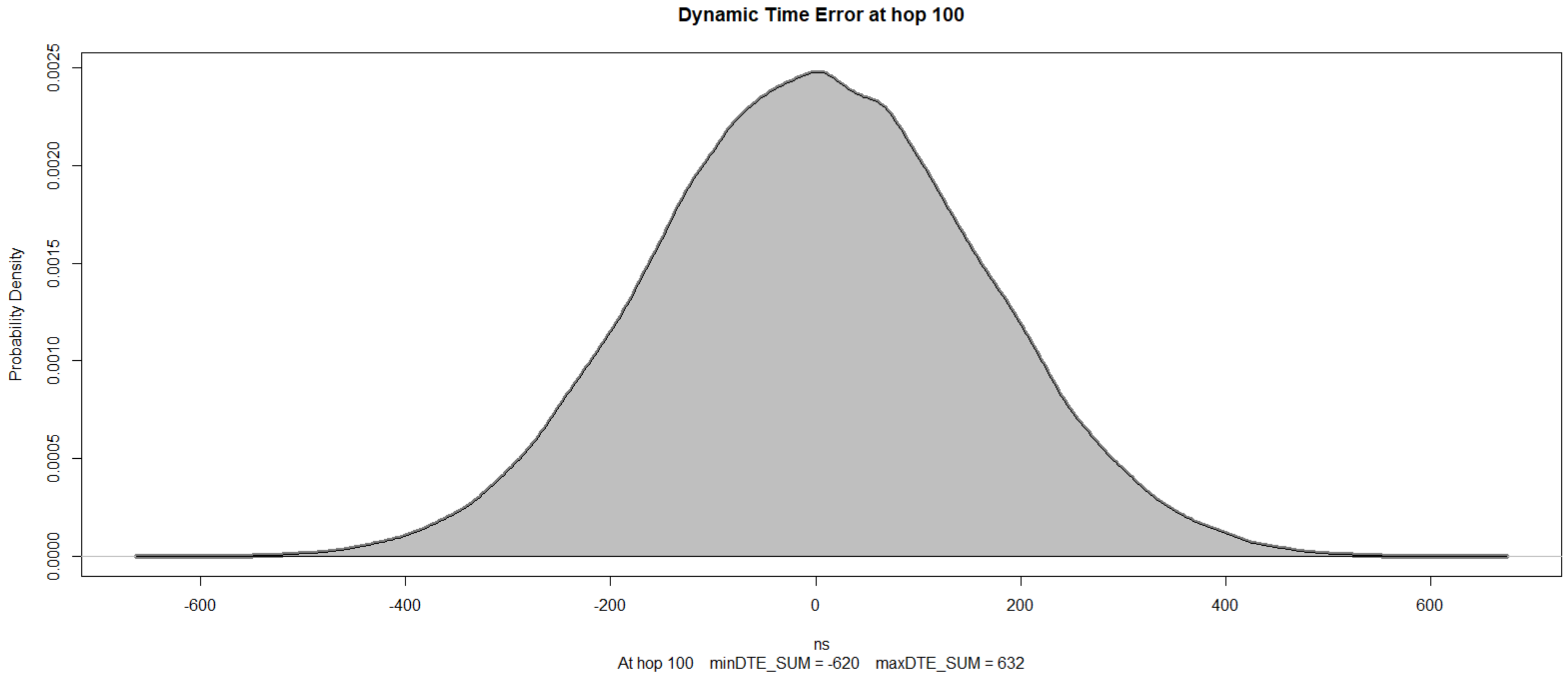
- Discussion during comment resolution of d1.1 that a normative requirement on meanLinkDelay accuracy is both possible and useful
  - meanLinkDelay is accessible via the relevant managed object (see IEEE 802.1AS-2020 14.16.6)
- There was no comment on d1.1 about this, so the discussion was deemed out of scope, but likely to be subject of comments on d1.2
  - May be rejected as out-of-scope for d1.2…but will then come back at SA Ballot

meanLinkDelay Normative Requirement?

- We could require performance equivalent to the steady state performance from the Monte Carlo simulation, but…
- That doesn’t take into consideration some other sources of meanLinkDelay error (e.g. Clock Drift and Timestamp Error affecting NRR estimation)
  - Effect is orders of magnitude less than direct Timestamp error
- Maybe overkill?
  - We already have normative requirements on overall error generation that cover accurate measurement of meanLinkDelay + residencetime
  - If meanLinkDelay algorithm is mostly effective, the impact of meanLinkDelay error will be swamped by other sources of error
- What level of meanLinkDelay error starts to have a negative impact on overall dTE?

100 Hops – MLDerrorSDx6 1.13 ns

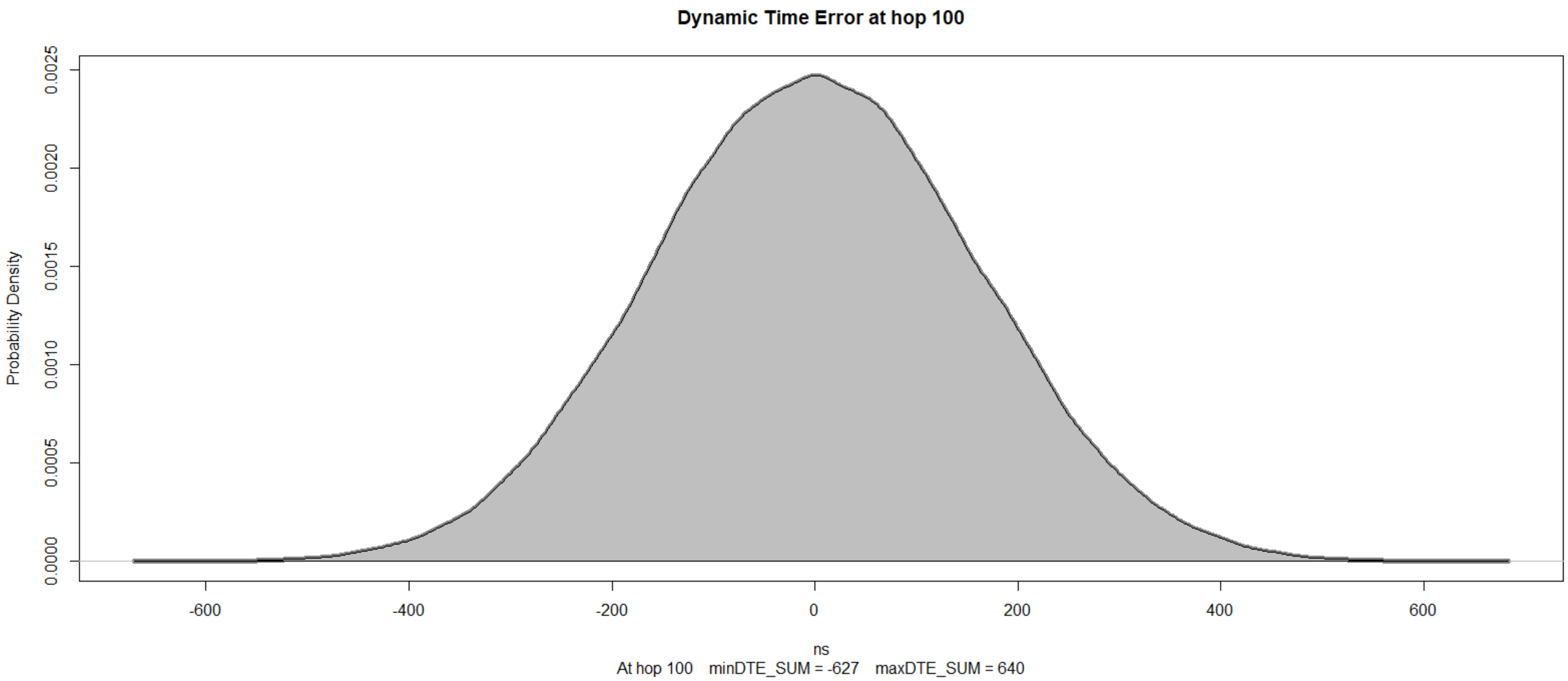
Recommended meanLinkDelay Algorithm – Steady State



minDTE_SUM = -620 ns   maxDTE_SUM = 632 ns   **sdDTE_SUM = 159 ns [σ]**

100 Hops – MLDerrorSDx6 5.55 ns

Recommended meanLinkDelay Algorithm – After 10 s



minDTE_SUM = -627 ns   maxDTE_SUM = 640 ns   **sdDTE_SUM = 159 ns [σ]**

Normative Requirement – meanLinkDelay

Suggestions & Questions

- Noting that…
  - 1 sample in approx. 500 million falls outside 6σ range
  - 1 sample in approx. 3.5 million falls outside 5σ range
  - No algorithm → OK algorithm is a big difference
  - A simple IIR filter with factor 100 can deliver 6σ range ±3.6 ns after 27 s
    - Equivalent 5σ range is ±3.0 ns
    - An IRR filter with factor 1,000 delivers 5σ range is ±2.5 ns
  - Going from 6σ Range 1.13 → 5.55 ns doesn’t have a large negative effect on dTE, given other sources of error.
- Suggest a normative requirement of ±3 ns
  - Give enough information in the informative annex about behaviour of the recommended algorithm for test spec to be written appropriately.

Thank you

Default Configuration

```
hops <- 100 # Minimum 1 hop
runs <- 100000
#
# Input Errors, Parameters & Correction Factors
driftType <- 3 # 1 = DO NOT USE - Historical - Uniform Probability Distribution between MIN & MAX ppm/s
          # 2 = Probability Based on Linear Temp Ramp
          # 3 = Probability Based on Half-Sinusoidal Temp Ramp
          # 4 = Probability Based on Quarter-Sinusoidal Temp Ramp
# Clock Drift Probability from Temp Curve & XO Offset/Temp Relationship
tempMax <- +85 # degC - Maximum temperature
tempMin <- -40 # degC - Minimum temperature
tempRampRate <- 1 # degC/s - Drift Rate for Linear Temp Ramp
tempRampPeriod <- 95 # s - Drift Period for Sinusoidal & Half-Sinusoidal Temp Ramps
tempHold <- 30 # s - Hold Period at MIN and MAX temps before next temp ramp down or up
GMscale <- 0.5 # Ratio of GM stability vs. standard XO. 1 is same. 0 is perfectly stable.
nonGMscale <- 1 # Ratio of non-GM (and non-ES) node stability vs. standard XO. 1 is same. 0 is perfectly stable.
```

Default Configuration

TSGEtx <- 4 # +/- ns - Error due to Timestamp Granularity on TX

TSGErx <- 4 # +/- ns - Error due to Timestamp Granularity on RX

DTSEtx <- 6 # +/- ns - Dynamic Timestamp Error on TX

DTSErx <- 6 # +/- ns - Dynamic Timestamp Error on RX

syncInterval <- 125 # ms - Nominal Interval between two Sync messages

SImode <- 3 # Mode for generating Tsync2sync *HARD CODED to MODE 3*

1 = Gamma Distribution, defaulting to 90% of Tsync2sync falling within 10% of the nominal syncInterval. Truncated at SImax (higher values above are reduced to SImax)

No truncation of low values

2 = Gamma Distribution, defaulting to 90% of Tsync2sync falling within 10% of the nominal syncInterval. Truncated at SImax (higher values are reduced to SImax)

Truncated at SImin (lower values are increased to SImin)

3 = Uniform, linear distribution between syncInterval x SImin and syncInterval x SImax

Default Configuration

```
SIscale <- 1 # Scaling factor for Mode 1 & 2 Tsync2sync vs regular distribution.
            # Scaling factor of 3 would mean 90% of Tsync2sync falling within 30% of the nominal syncInterval
SImax <- 1.048    # For mode 1 & 2, Max truncation factor (e.g. 2x syncInterval) limit for Tsync2sync; higher values reduced to SImax
                  # For mode 3, upper limit of uniform linear distribution
SImin <- 0.952    # For mode 1 & 2, Min truncation factor (e.g. 0.5 x syncInterval) limit for Tsync2sync; higher values reduced to SImin
                  # For mode 3, lower limit of uniform linear distribution
pathDelayMin <- 5 # ns - 1m cable = 5ns path delay
pathDelayMax <- 500 # ns - 100m cable = 500ns path delay
residenceTime <- 15 # ms - TresidenceTime maximum; higher values truncated
RTmin <- 1 # TresidenceTime minimum; lower values truncated
RTmean <- 5 # TresidenceTime mean
RTsd <- 1.8 # TresidenceTime sigma; 3.4ppm will fall outside 6-sigma either side of the mean
```

Default Configuration

```
MLDerrorSDx6 <- 1.13 # ns - 6x Standard Deviation of meanLinkDelay Error
                # Calculated from separate simulation.
                # 1.13 ns is for steady state after IIR filter with alpha = 1000 has stabalised
mNRRsmoothingNA <- 4 # Whole Number >=1 - Combined N & A value for "smoothing" calculated mNRR (mNRRc)
                # Calculate mNRR using timestamps from Nth Sync message in the past
                # Then take average of previous A mNRRcalculations.
mNRRcompNAP <- 8 # Whole Number >=1
             # For NRR drift rate error correction calculations, take two measurements, mNRRa and mNRRb.
             # Both use timestamps from Nth Sync message in the past, then take average of previous A calculations.
             # Calculation mNRRb starts P calculations in the past from mNRRa, where P = mNRRcompNAP * 2.
             # If 0, there is no NRR drift rate error correction.
```