Further Simulation Results for Dynamic Time Error Performance for Transport over an IEC/IEEE 60802 Network Based on Updated Assumptions
Revision 2

Geoffrey M. Garner
Huawei (Consultant)

gmgarner@alum.mit.edu

IEEE 802.1 TSN TG
2020.12.14

Outline

- Introduction
- Summary of Assumptions for Simulation Cases
- Results
- Conclusion and Discussion of Next Steps

- New or revised slides for Revision2:
  - 2 (this slide), 5 – 7, 47 (fixed typo in headings of last 2 columns), 49 – 64, 66 – 67

Introduction - 1

- New simulations results for dynamic time error performance for transport over an IEC/IEEE 60802 network are presented in [1]
  - An initial version of this presentation was presented at the September, 2020 IEC/IEEE 60802 meeting
  - This included 6 simulation cases
    - 3 cases where GM rateRatio was measured by accumulating neighborRateRatio
    - 3 cases where GM rateRatio was measured using successive Sync messages
    - While some of the cases gave acceptable dTE_R performance (relative to the GM) for a Hypothetical Reference Model (HRM) consisting of 65 nodes (64 hops), those cases assumed residence times of either 1 ms or 4 ms
    - dTE_R performance for 10 ms residence time was either marginal or unacceptable
  - After discussion of [1], it was decided to consider two additional simulation cases
    - These cases were run, and the results were presented in a subsequent IEC/IEEE 60802 virtual meeting/call
    - However, the new results showed dTE performance that was similar to one of the cases of [1] whose results were marginal
- Based on the above results, it was decided to consider three new cases
  - Two of the new cases assume an oscillator with improved performance, and the third new case is a minor modification of one of the cases of [1] that gave acceptable performance (4 ms residence time)

Introduction - 2

- The current presentation includes simulation results for the three new cases
- In addition, when preparing the new simulations, it was found that the previous simulations did not properly account for the ± 8 ns dynamic timestamp error for event messages due to variable delays within the PHY (see slide 13 of [1] and slide 14 of [2])
  - The simulations did not add this error on receipt of a Sync message
  - This was fixed, and the previous simulation cases were re-run, in addition to the three new cases

Introduction for Revision 2 - 1

- Revision 2 adds the following new and revised results
  - Simulation results for max|dTE_R| relative to GM, for the case where the GM dynamic time error is non-zero, for cases 9, 10, and 11
  - New simulation cases 12, 13, and 14 (max|dTE_R| for both zero and non-zero GM dynamic time error)
- For the cases where GM dynamic time error is non-zero, it was noted earlier that care must be taken to avoid errors due to insufficient precision, because the magnitudes of the GM dynamic time error and the total accumulated dynamic time error are each much larger than the relative dynamic time error between a downstream time-aware system and the GM
  - The computation of relative time error was done as a post-processing operation, first interpolating the GM and downstream dTEs to the same sampling times, and then computing the difference in the two time histories
  - Sufficient precision was maintained by reading and writing simulation results to a precision of 11 significant digits
    - This is sufficient, because the amplitude of the GM time error waveform is approximately 830 μs (see [11]), and dTE_R is on the order of hundreds of ns or more (even if dTE_R were on the order of 1 ns, dTE_R would only be 6 orders of magnitude less than GM time error amplitude)

Introduction for Revision 2 - 2

- However, even after maintaining this level of precision, the initial simulations of dTE_R for the case of non-zero GM time error were giving results that were much too large (by a few orders of magnitude)
- After some investigation, the problem was found to be due to an error in the endpoint filter model implementation
  - A term in one of the filter equations was missing; the effect of this was to produce an end point filter with the same bandwidth and gain peaking, but with 40 dB/decade roll-off instead of 20 dB/decade roll-off
  - The error was simple to fix; note that this error was not present in any of the previous simulations where damping ratio is greater than 1
    - This includes almost all the simulations run prior to the present simulations (i.e., over approximately 20 years or more); the present simulations are the first simulations considered where damping ratio is greater than 1
    - The filter model is based on the model in Appendix VIII/ITU-T Rec. G.8251; that model assumes damping ratio is greater than 1 (because in telecom networks with chains of clocks, gain peaking must be controlled)
    - The filter model was modified to cover the case of damping ration less than 1, and this is where the error was introduced

Introduction for Revision 2 - 3

- Unfortunately, at the point when the error was diagnosed and corrected (approximately 2.5 days before the present meeting), there was insufficient time to rerun 300 multiple replications for the new simulation cases (9 – 11, 12 – 14)
- Therefore, the new results in the present presentation (Revision 2) are based on a single replication
- If desired, 300 multiple replications can be run, and the results can be presented in a future meeting

Summary of Assumptions for Simulations - 1

- In the following slides, the assumptions are summarized, mainly by repeating the summary of [1], [2], and [10] (with some corrections)
- Detailed background on the different assumptions are given in [3] – [9], but note the following points
  - Local clock phase and frequency variation is assumed to be sinusoidal
  - 300 multiple replications of each simulation case are performed, with random (independent) initial conditions for each replication; in particular
    - Initial phases of each Local Clock (including the GM in cases where the GM time and frequency error is modeled) are chosen randomly in [0, 2π]
    - Initial frequencies of each Local Clock (including the GM in cases where the GM time and frequency error is modeled) are chosen randomly in the range [50 - ε, 50] ppm, with ε = 5 ppm and maximum frequency drift rate of 3 ppm/s
      - This allows the modulation frequency (i.e., the frequency of the phase and frequency variation waveform to vary over a 10% range (i.e., (5 ppm/50 ppm))
- For each of 11 simulation cases (described shortly), 2 subcases were described in [1] and [2]
  - Source of GM time is assumed to be zero (though GM still has timestamp granularity), and max|dTE| is simulated
  - Source of GM time has same error as Local Clocks, and max|dTE_R| relative to GM is simulated

Summary of Assumptions for Simulations – 2

- For cases where source of GM time has non-zero error, max|dTE_R| should be computed using linear interpolation, because Sync message transmission times at the successive clocks (and therefore times at which time errors are computed at the successive clocks) are, in general, not the same
- Note that dTE_R relative the GM is actually relative to the PTP output of the GM, and therefore does not include timestamp granularity at the GM output
  - Possibly dTE_R should have included timestamp granularity at the GM output; in any case, it will be seen that timestamp granularity (2 ns) is negligible compared to max|dTE_R| results (larger than 4 μs)
- The following slides repeat the tables of assumptions from [8], and then summarize some of the details of the assumptions that were described in [1]
- Following that, we first present results, i.e., max|dTE|, for each simulation case assuming the error in the source of GM time is zero
- An approximate analysis for the case where the source of GM time has nonzero error was given in [1] and [2]
  - Based on discussion in the September 2020 IEC/IEEE 60802 meeting and in a subsequent meeting/call, the analysis has been improved, and is contained in a companion presentation [11]
  - Simulation results for the case where GM time error is nonzero will be given in a future presentation

Assumptions Common to All Simulation Cases - 1

Assumption/Parameter	Description/Value
Hypothetical Reference Model (HRM), see note following the tables	101 PTP Instances (100 hops; GM, followed by 99 PTP Relay Instances, followed by PTP End Instance
Timestamp granularity	2 ns
GM maximum frequency offset	0 (for now, the effect of a ± 50 ppm frequency offset is considered in the approximate analysis of [11])
GM maximum frequency drift rate	0 (for now, the effect of a 3 ppm/s frequency maximum frequency drift rate is considered in the approximate analysis of [11])
PTP End/Relay Instance maximum frequency offset (Local Clock)	± 50 ppm
PTP End/Relay Instance maximum frequency drift rate (Local Clock)	3 ppm/s (cases 1 – 9) 0.3 ppm/s (case 10) 3 ppm/s and 0.3 ppm/s alternating (case 11)
GM and Local Clock frequency variation	sinusoidal
Relative phases of GM and Local Clock frequency waveforms	Chosen randomly from a uniform distribution over [0, 2π] rad at initialization
Relative frequencies of Local Clock frequency waveforms	Choose randomly at initialization by allowing waveform amplitude to be random over a range [50 - ε, 50] ppm; choose ε = 5 ppm, so that the waveform frequency varies over a 10% range

Assumptions Common to All Simulation Cases - 2

Assumption/Parameter	Description/Value
Computed performance results	$\max\|dTE_{R(k,\,0)}\|$ (i.e., maximum absolute relative time error between node k ($k > 0$) and GM; here, GM time error is 0, so $\max\|dTE_{R(k,\,0)}\| = \max\|dTE\|$)
Use syncLocked mode for PTP Instances downstream of GM	Yes
Window size for successive Sync messages method, when used	7 (take difference between respective timestamps of current Sync message and 7th previous message)
Compute median for successive Sync messages method, when used	Yes
Endpoint filter parameters	$K_pK_o = 11$, $K_iK_o = 65$ ($f_{3dB} = 2.5998$ Hz, 1.288 dB gain peaking, $\zeta = 0.68219$)
Simulation time	1050 s; discard first 50 s to eliminate any startup transient before computing $\max\|dTE_{R(k,\,0)}\|$
Number of independent replications, for each simulation case	300
GM rateRatio and neighborRateRatio computation granularity	0
Mean link delay	500 ns
Link asymmetry	0

Assumptions Common to All Simulation Cases - 3

Assumption/Parameter	Description/Value
Dynamic timestamp error for event messages (Sync, Pdelay-Req, Pdelay_Resp) due to variable delays within the PHY	±8 ns; for each timestamp taken, a random error is generated. The error is + 8 ns with probability 0.5, And – 8 ns with probability 0.5. The errors are independent for different timestamps and different PTP Instances. Note: This error was not properly accounted for in the simulations of [1] and [2]
Window Size for mean link delay averaging (i.e., how many mean link delay samples are averaged over, assuming a sliding window)	16

Summary of Simulation Cases (parameters that are different for each case) - 1

Case	Method of computing GM rateRatio	Maximum frequency drift rate of local clock (ppm/s)	Residence time (ms)	Pdelay turnaround time (ms)	Mean Sync Interval (ms)	Mean Pdelay Interval (ms)
1	Accumulate neighborRateRatio	3	1	1	125	31.25
2	Accumulate neighborRateRatio	3	4	4	125	31.25
3	Accumulate neighborRateRatio	3	10	10	125	31.25
4	Use successive Sync messages	3	1	10	31.25	1000
5	Use successive Sync messages	3	4	10	31.25	1000
6	Use successive Sync messages	3	10	10	31.25	1000

Note that the mean Sync interval in cases 1 – 3 was mistakenly indicated as 0.125 ms in [10]; this was an error (typo)

Summary of Simulation Cases (parameters that are different for each case) - 2

Case	Method of computing GM rateRatio	Maximum frequency drift rate of local clock (ppm/s)	Residence time (ms)	Pdelay turnaround time (ms)	Mean Sync Interval (ms)	Mean Pdelay Interval (ms)
7	Accumulate neighborRateRatio	3	10	1	125	31.25
8	Accumulate neighborRateRatio	3	10	4	125	31.25
9	Accumulate neighborRateRatio (Note 2 on next slide)	3	4	10	125	31.25
10	Accumulate neighborRateRatio (Note 2 on next slide)	0.3	10	10	125	31.25
11	Accumulate neighborRateRatio (Note 2 on next slide)	3 and 0.3, alternating (after node 1 (GM), nodes 2, 4, 6, …, 100 have 3 ppm/s, and nodes 3, 5, …, 101 have 0.3 ppm/s)	4 and 10, alternating (after node 1 (GM), nodes 2, 4, 6, …, 100 have 4 ms, and nodes 3, 5, …, 101 have 10 ms)	10	125	31.25

Summary of Simulation Cases (parameters that are different for each case) - 3

Case	Method of computing GM rateRatio	Maximum frequency drift rate of local clock (ppm/s)	Residence time (ms)	Pdelay turnaround time (ms)	Mean Sync Interval (ms)	Mean Pdelay Interval (ms)
12	Use successive Sync messages (Notes 1, 2)	3	1	10	31.25	1000
13	Use successive Sync messages (Note 1, 2)	3	4	10	31.25	1000
14	Use successive Sync messages (Note 1, 2)	3	10	10	31.25	1000

Note 1: In cases 12, 13, and 14, the window size for both Sync (rate ratio calculation) and Pdelay (neighborRateRatio calculation, needed to correct meanLinkDelay for neighborRateRatio) is 12 (current message and previous 11 messages) rather than 8 (current message and previous 7 messages) used in Cases 4 – 6.

Note 2: Single replications of simulations were run for cases 9 – 14, for both The cases of zero and non-zero GM Time error, with the corrected endpoint Filter (see slides 6 and 7)

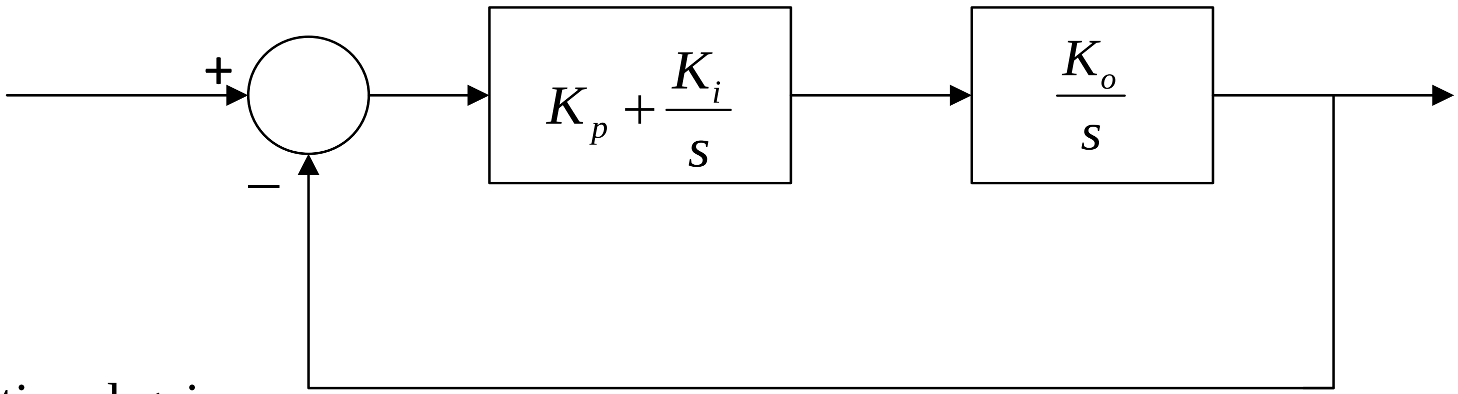
Review of Assumptions for HRM – 1

- As in previous simulations, the HRM is a linear chain that consists of 101 PTP Instances, and therefore with 100 PTP links connecting each successive pair of PTP Instance
  - The first PTP Instance in the chain is the Grandmaster PTP Instance
  - The next 99 PTP Instances are PTP Relay Instances
  - The last PTP Instance is a PTP End Instance
  - The PTP End Instance contains an endpoint filter, through which the transported time is computed

Assumptions for HRM - 2

- As in previous simulations, the GM and each PTP Relay Instance do not filter the timestamps with an endpoint filter when computing the value of the originTimestamp and correctionField of each transmitted Sync message
  - Rather, these fields are computed using the same fields of the most recently received Sync message, the <syncEventIngressTimestamp> of the most recently received Sync message, the <syncEventEgressTimestamp of the Sync message being transmitted, and the current value of rateRatio (i.e., cumulative rateRatio)
- However, the information at each PTP Relay Instance is used to separately compute a filtered (recovered) time, which could be used, e.g., by a co-located end application
  - This is equivalent to having a PTP End Instance collocated with the PTP Relay Instance

Review of Endpoint Filter Model and Assumptions - 1



$K_p =$ proportional gain

$K_i =$ integral gain

$K_o =$ VCO/DCO gain

Transfer function:

$$H(s) = \frac{K_p K_o s + K_i K_o}{s^2 + K_p K_o s + K_i K_o} = \frac{2\varsigma\omega_n s + \omega_n^2}{s^2 + 2\varsigma\omega_n s + \omega_n^2}$$

with

$$\omega_n = \sqrt{K_i K_o} \qquad \varsigma = \frac{K_p}{2}\sqrt{\frac{K_o}{K_i}}$$

Review of Endpoint Filter Model and Assumptions - 2

- Often the filter parameters (and requirements) are expressed in terms of 3 dB bandwidth ($f_{3\text{dB}}$) and gain peaking (H_p)
  - These are related to damping ration (ζ) and undamped natural frequency (ω_n) by (see [6] and [7] of reference [2] here):

$$f_{3\text{dB}} = \frac{\omega_n}{2\pi}\left[1 + 2\varsigma^2 + \sqrt{\left(1 + 2\varsigma^2\right)^2 + 1}\right]^{1/2}$$

$$H_p(\text{dB}) = 20\log_{10}\left\{\left[1 - 2\alpha - 2\alpha^2 + 2\alpha\sqrt{2\alpha + \alpha^2}\right]^{-1/2}\right\}$$

where

$$\alpha = \frac{1}{4\varsigma^2} = \frac{K_i}{K_p^2 K_o}$$

Endpoint Filter Model and Assumptions – 3

- As in previous simulation models, the VCO gain was folded into the proportional gain and integral gain (this is equivalent to setting the VCO gain to 1)
- Filter assumption:
  - $K_p K_o = 11$, $K_i K_o = 65$
  - Using the equations on the previous slides, we obtain
    - $\zeta = 0.68219$
    - $\omega_n = 8.06226$ rad/s ≈ 8.06 rad/s
    - H_p (gain peaking) = 1.28803 dB = (approx) 1.3 dB
    - $f_{3dB} = 2.5998$ Hz ≈ 2.6 Hz
- Note that this filter is underdamped, and has appreciable gain peaking
  - However, the damping ratio (ζ) is close to $1/\sqrt{2}$ = (approx) 0.707); this is often used to obtain a fast response with small overshoot, in cases where the filters are not cascaded (the endpoint filters are not cascaded)

Review of computation of GM rateRatio using successive Sync messages - 1

- These assumptions are used in cases 4, 5, and 6 for measurement of GM rateRatio using successive Sync messages (but not for new cases 9, 10, and 11)
- Assume the computation is done every Sync message, using a window of size n (i.e., a sliding window)
  - The computation is done on ingress of a Sync message at a PTP Instance
  - The window size n includes the current Sync message (e.g., a window of size 8 consists of the current Sync message and the previous 7 Sync messages)
- Let C_{kn} be the correctedMasterTime carried by Sync message kn
- Let S_{kn} be the SyncEventIngressTimestamp for Sync message kn
- Then the initial computed $\mathrm{rateRatio}$ is

$$\mathrm{rateRatio}_{kn} = \frac{C_{kn} - C_{(k-1)n}}{S_{kn} - S_{(k-1)n}}$$

- Note that frequency offset is equal to $\mathrm{rateRatio} - 1$
- The above computation is performed for every Sync message that arrives at a PTP Instance

Review of computation of GM rateRatio using successive Sync messages - 2

- Finally, the median of the current and previous $n - 1$ computed values of initial GM rateRatio is obtained
  - The median is computed by sorting the n values from smallest to largest and taking the p^{th} smallest value, where $p = \text{floor}\,(n) + 1$
- For the simulations, we use the median

Computation of neighborRateRatio (new)

- In computing neighborRateRatio, the same methodology is used as described in the previous two slides for the computation of GM rateRatio, except
  - C_{kn} is replaced by correctedResponderEventTimestamp (see 11.2.19.3.3 of IEEE Std 802.1AS-2020) of peer delay exchange kn
  - S_{kn} is replaced by the pdelayRespEventIngressTimestamp of the Pdelay_Resp message of peer delay exchange kn
- The median of the current and previous $n - 1$ computed values of initial neighborRateRatio is obtained
  - The median is computed by sorting the n values from smallest to largest and taking the p^{th} smallest value, where $p = \text{floor}\,(n) + 1$
- For the simulations, we use the median

Revised Results for dTE_R for Previous Cases (1 - 8) - 1

- The following plots show results for cases 1 – 8 (results for cases 9 – 11 are in subsequent slides)
  - Max|dTE_R|, cases 1 – 6, nodes 2 – 100, 99% confidence intervals for 0.95 quantile, and maximum over 300 replications
  - Max| dTE_R |, cases 1 – 6, nodes 2 – 100, maximum over 300 replications (less cluttered than previous plot)
  - Max| dTE_R |, cases 1 – 6, nodes 2 – 65, 99% confidence intervals for 0.95 quantile, and maximum over 300 replications
  - Max| dTE_R |, cases 1 – 6, nodes 2 – 65, maximum over 300 replications (less cluttered than previous plot)
  - Max|dTE_R|, cases 7 – 8, nodes 2 – 100, 99% confidence intervals for 0.95 quantile, and maximum over 300 replications
  - Max| dTE_R |, cases 7 – 8, nodes 2 – 100, maximum over 300 replications (less cluttered than previous plot)
  - Max| dTE_R |, cases 1, 2, 3, 7, 8, nodes 2 – 100, maximum over 300 replications (these cases are shown on the same plot, for comparison; only maximum is shown so that the plot is less cluttered)

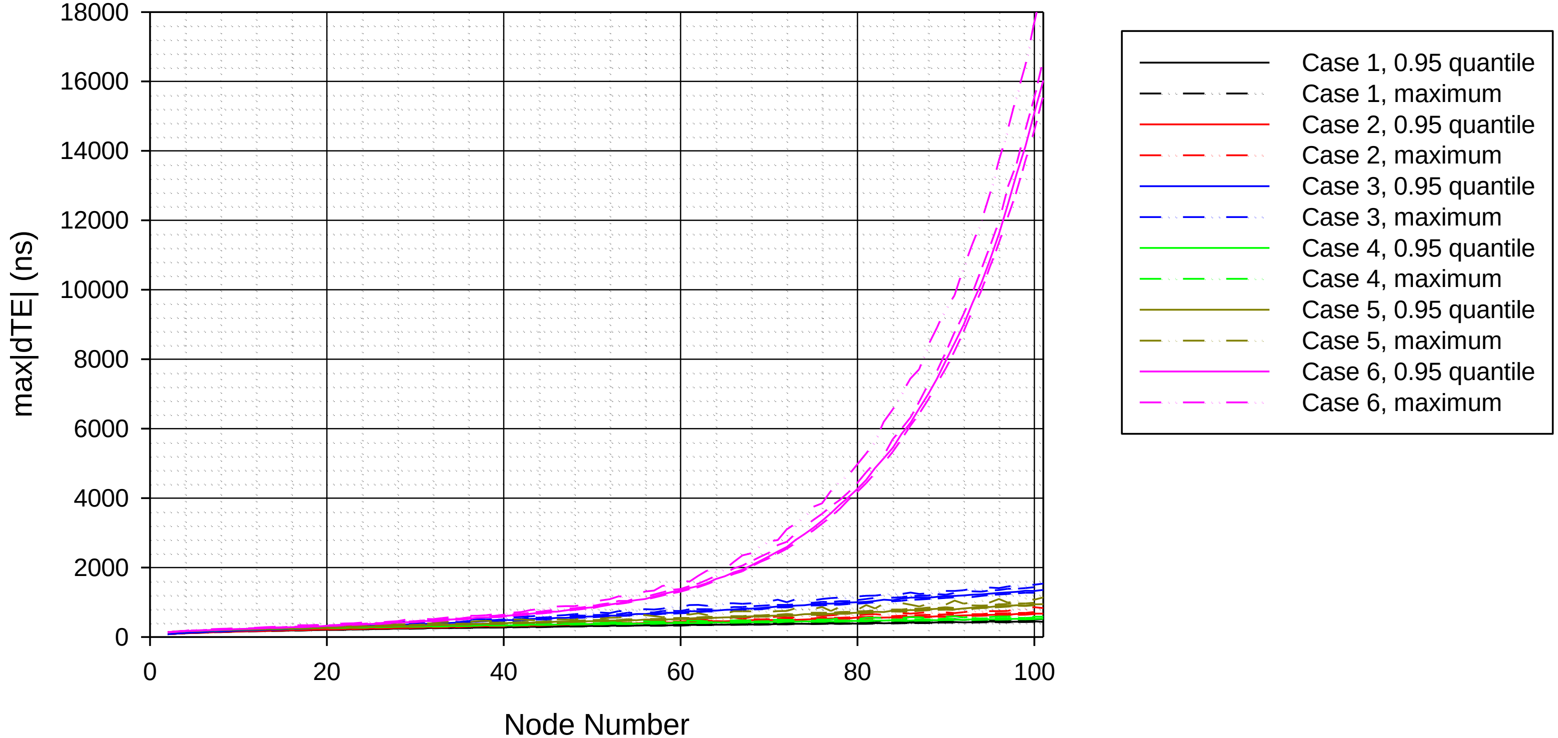
Revised Results for dTE_R for Previous Cases (1 - 8) - 2

- There are two plots for each of the above
  - The first plot contains the new (revised) results
  - The second plot contains the results from [1] and [2]
- As indicated in the Introduction (slide 4) and in the table of assumptions (slide 9), the results in [1] and [2] did not properly account for the ± 8 ns dynamic timestamp error for event messages due to variable delays within the PHY
  - Also, the results in [1] and [2] for cases 1 – 6 used an incorrect PLL (endpoint filter) integral gain parameter(249 instead of 65; see [1] and [2]) for the endpoint filter

Revised Results for dTE_R for Previous Cases (1 - 8) - 3

Simulation Cases 1 - 6
300 replications of simulation
Upper and lower 99% confidence intervals shown via short dashed lines
Clock Model: sinusoidal phase and freqeuncy variation
- 50 ppm max freq offset
- 3 ppm/s maximum drift rate
- relative phases of modulation chosen randomly over [0,2*pi] on initialization
- Actual modulation amplitude chosen randomly over [45 ppm, 50 ppm]

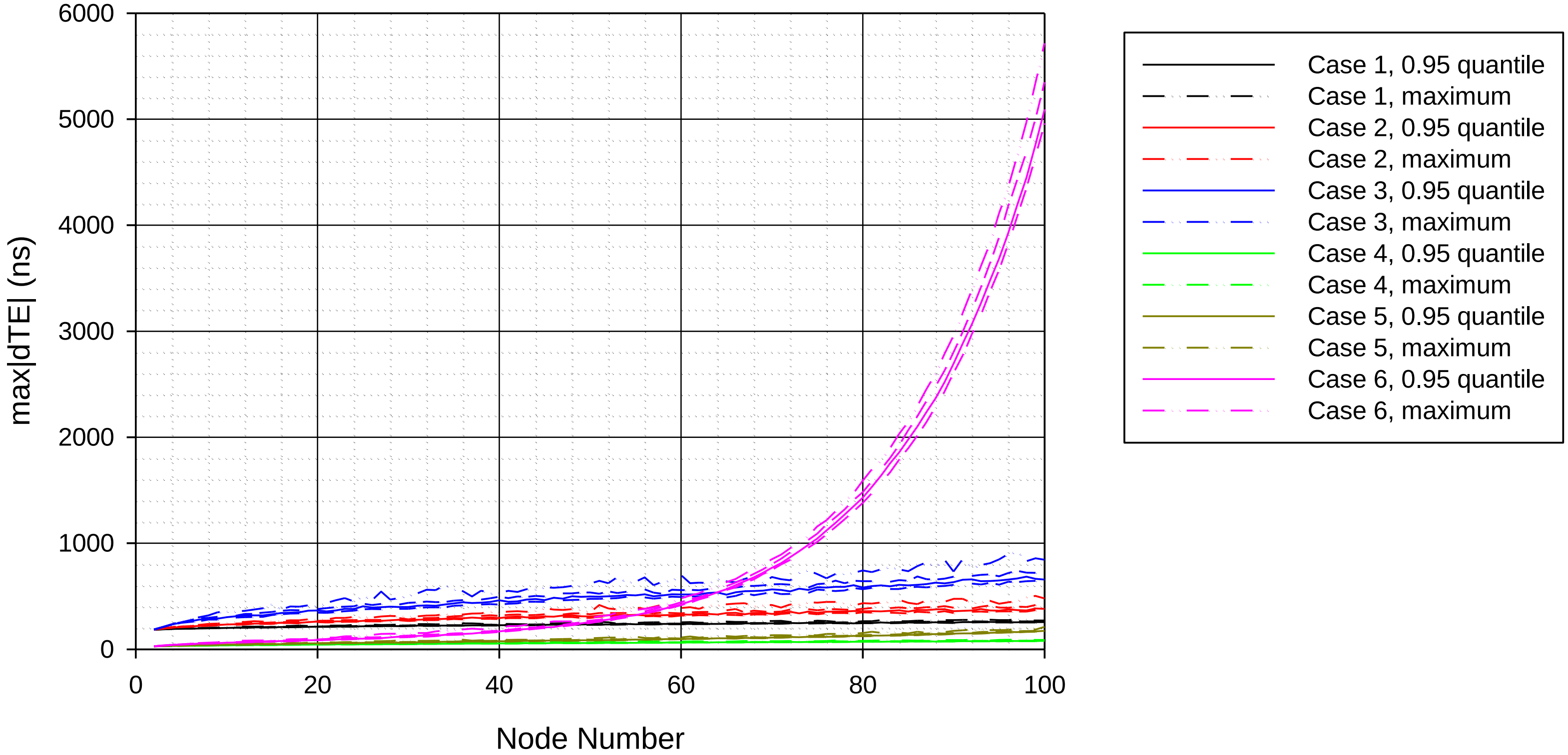
Cases 1 - 3: accumulate neighborRateRatio
Cases 4 - 6: measure GM rate ratio using successive Sync msgs



Results for dTE, Zero Error in GM Time Source (previous results, from [2]) - 4

Simulation Cases 1 - 6
300 replications of simulation
Upper and lower 99% confidence intervals shown via short dashed lines
Clock Model: sinusoidal phase and freqeuncy variation
- 50 ppm max freq offset
- 3 ppm/s maximum drift rate
- relative phases of modulation chosen randomly over [0,2*pi] on initialization
- Actual modulation amplitude chosen randomly over [45 ppm, 50 ppm]

Cases 1 - 3: accumulate neighborRateRatio
Cases 4 - 6: measure GM rate ratio using successive Sync msgs

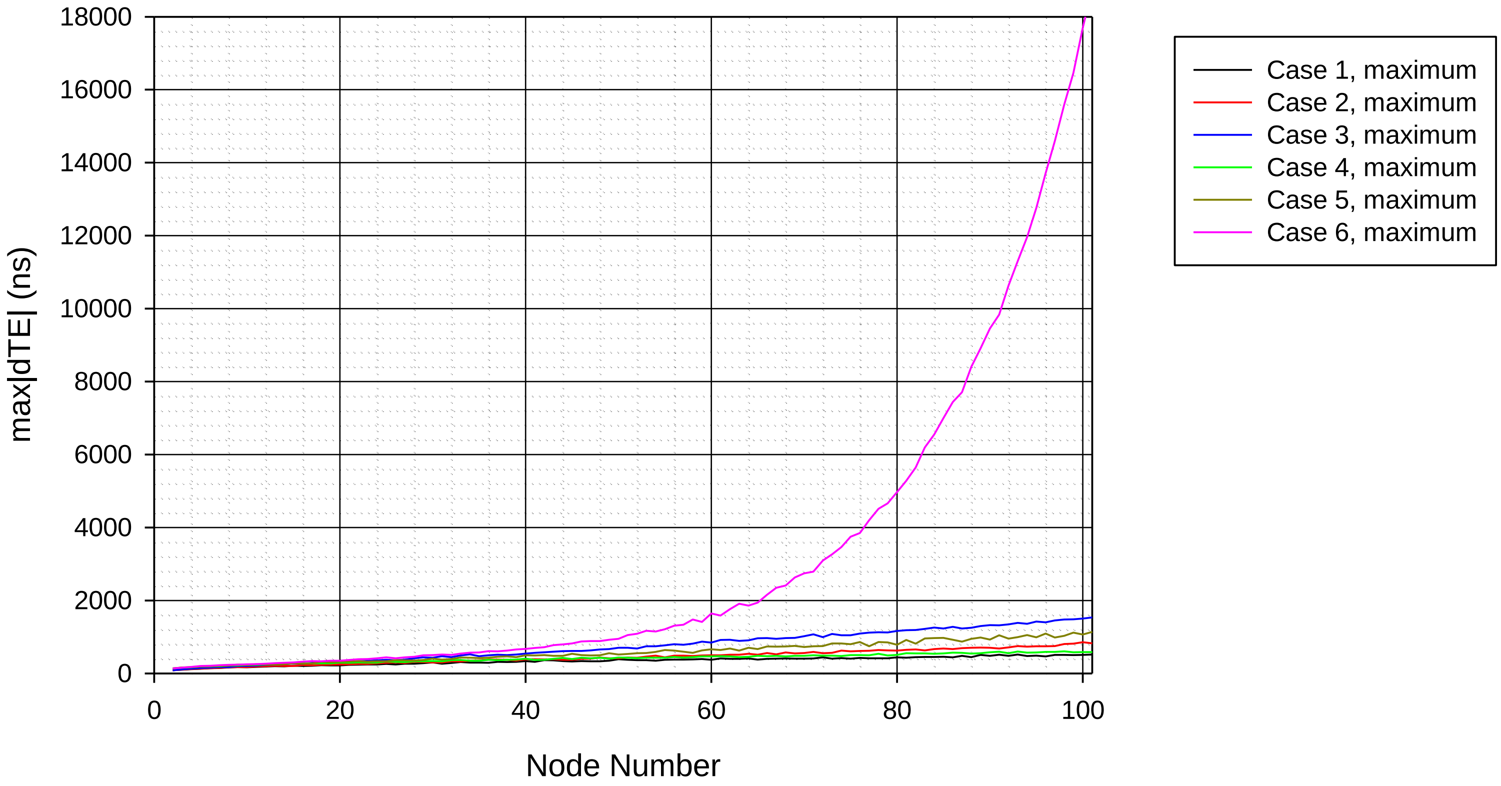


Revised Results for dTE_R for Previous Cases (1 - 8) - 5

Simulation Cases 1 - 6
300 replications of simulation
Clock Model: sinusoidal phase and freqeuncy variation

- 50 ppm max freq offset
- 3 ppm/s maximum drift rate
- relative phases of modulation chosen randomly over [0,2*pi] on initialization
- Actual modulation amplitude chosen randomly over [45 ppm, 50 ppm]

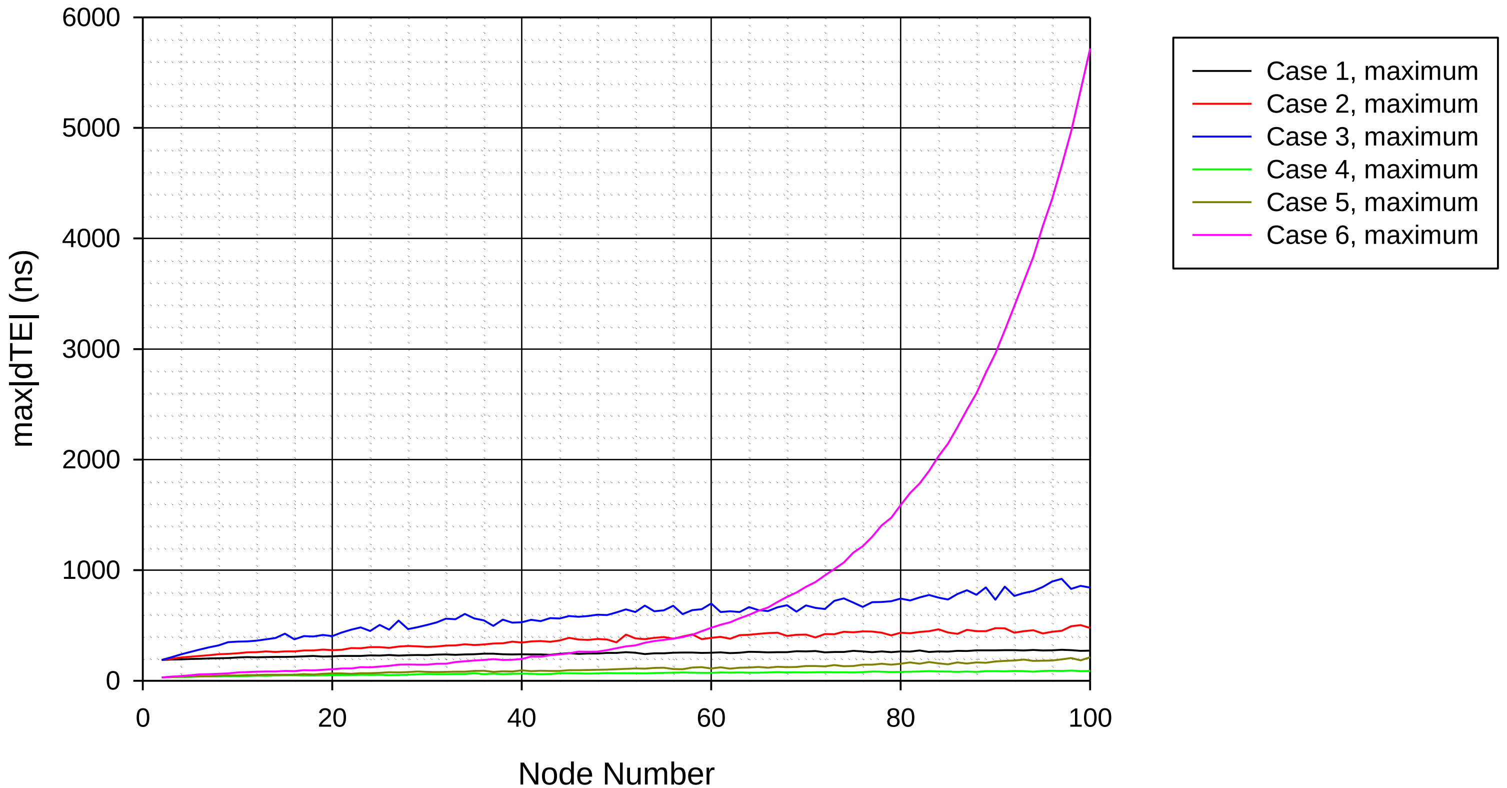
Cases 1 - 3: accumulate neighborRateRatio
Cases 4 - 6: measure GM rate ratio using successive Sync msgs



Results for dTE, Zero Error in GM Time Source (previous results, from [2]) - 6

Simulation Cases 1 - 6
300 replications of simulation
Clock Model: sinusoidal phase and freqeuncy variation
- 50 ppm max freq offset
- 3 ppm/s maximum drift rate
- relative phases of modulation chosen randomly over [0,2*pi] on initialization
- Actual modulation amplitude chosen randomly over [45 ppm, 50 ppm]

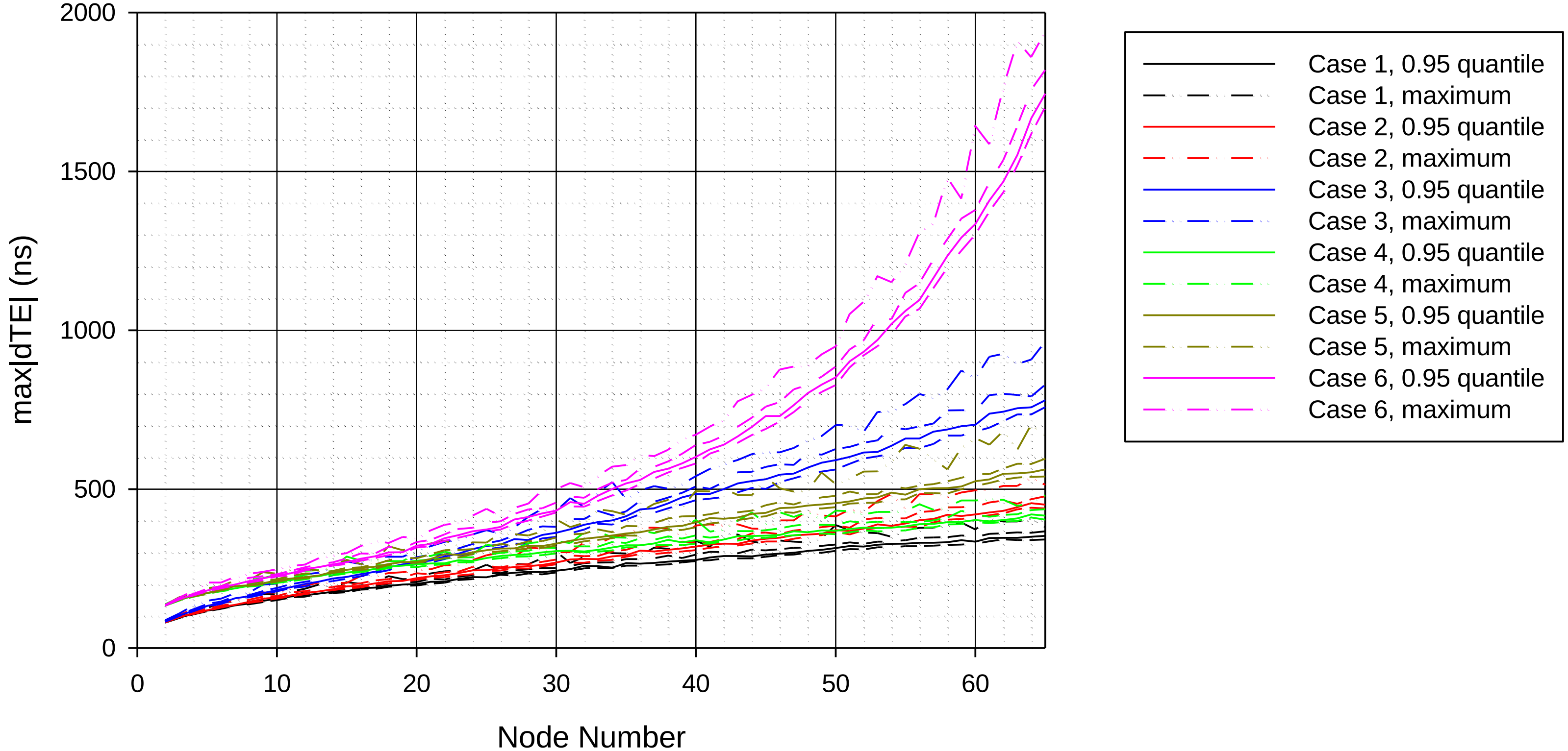
Cases 1 - 3: accumulate neighborRateRatio
Cases 4 - 6: measure GM rate ratio using successive Sync msgs



Revised Results for dTE_R for Previous Cases (1 - 8) - 7

Simulation Cases 1 - 6
300 replications of simulation
Upper and lower 99% confidence intervals shown via short dashed lines
Clock Model: sinusoidal phase and freqeuncy variation
- 50 ppm max freq offset
- 3 ppm/s maximum drift rate
- relative phases of modulation chosen randomly over [0,2*pi] on initialization
- Actual modulation amplitude chosen randomly over [45 ppm, 50 ppm]

Cases 1 - 3: accumulate neighborRateRatio
Cases 4 - 6: measure GM rate ratio using successive Sync msgs

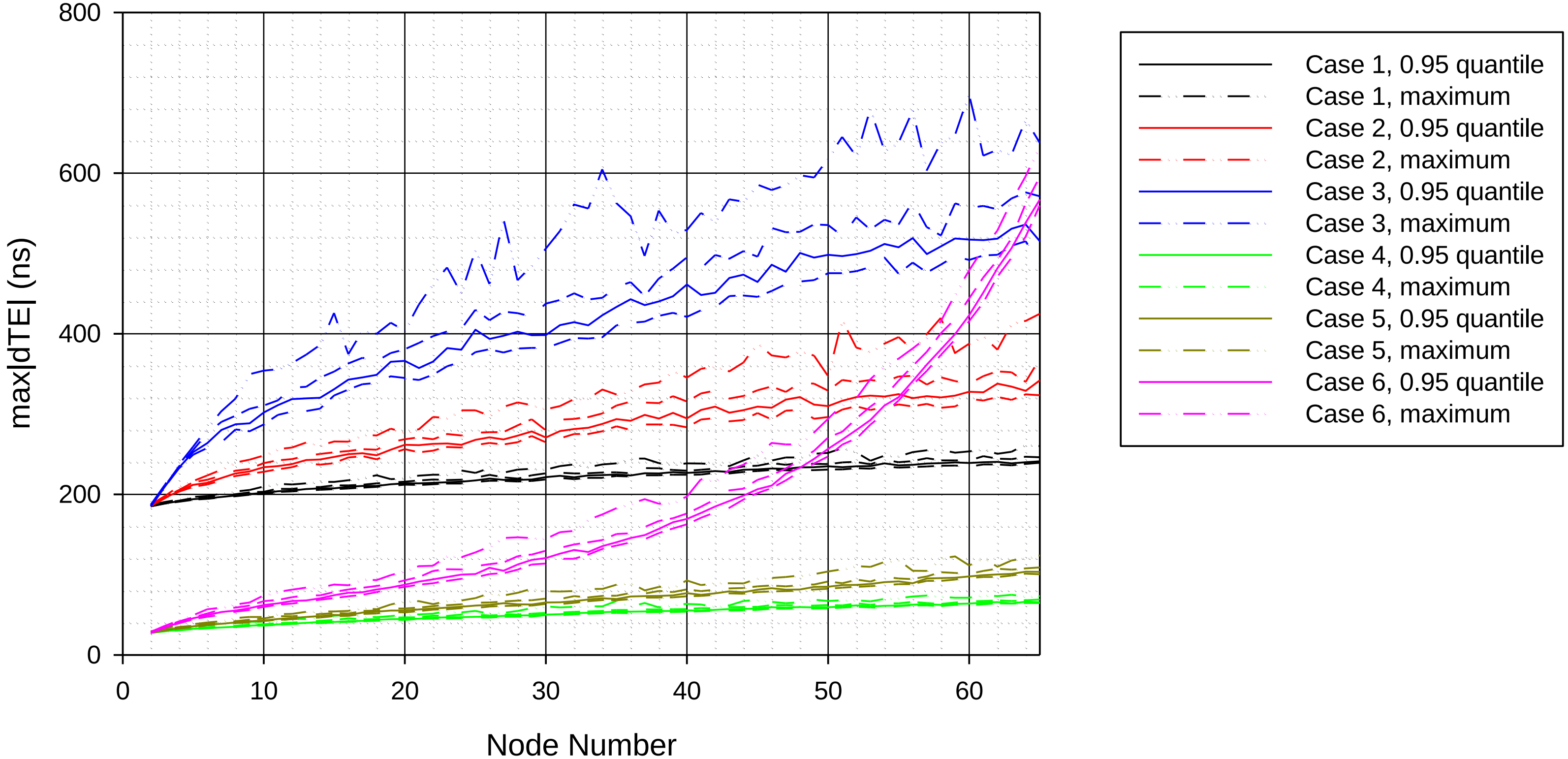


Results for dTE, Zero Error in GM Time Source (previous results, from [2]) - 8

Simulation Cases 1 - 6
300 replications of simulation
Upper and lower 99% confidence intervals shown via short dashed lines
Clock Model: sinusoidal phase and freqeuncy variation

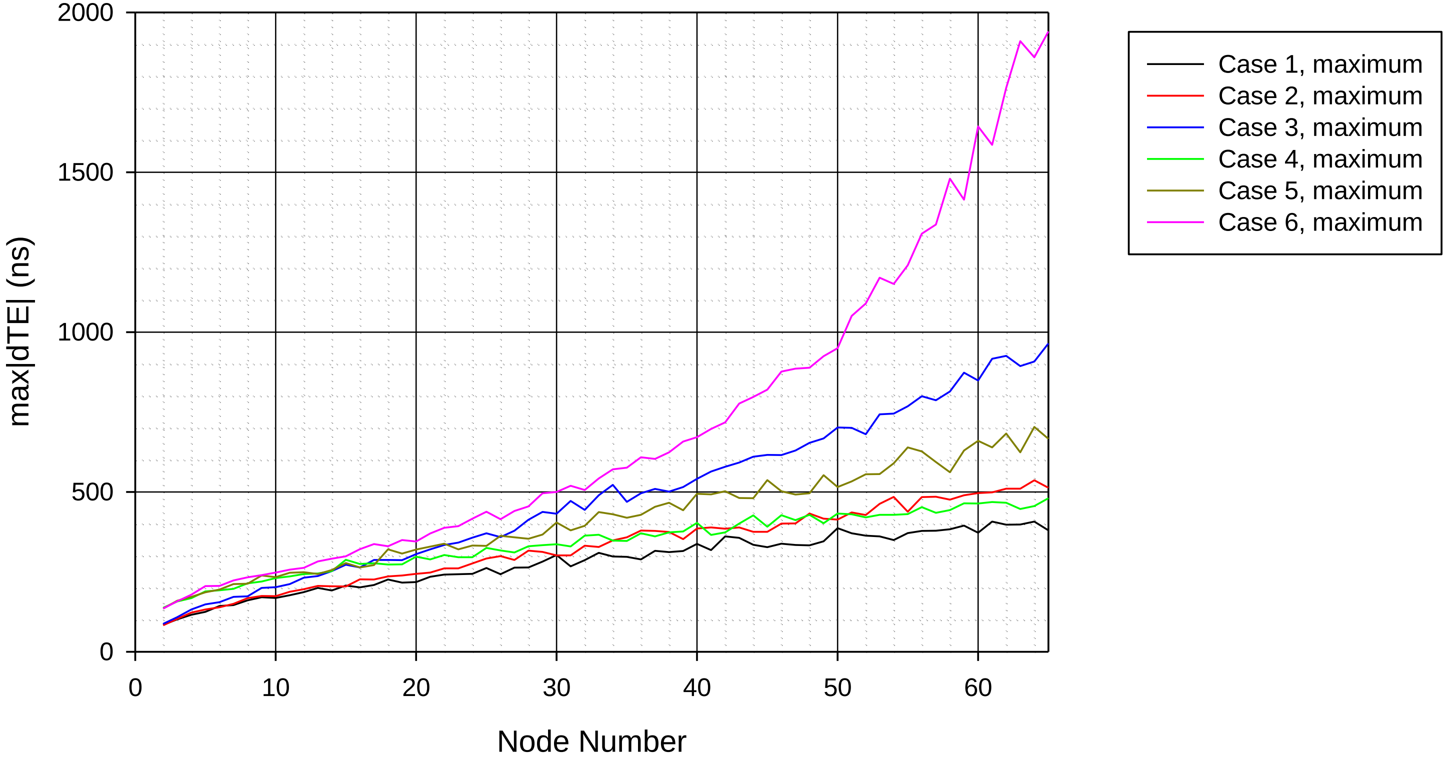
- 50 ppm max freq offset
- 3 ppm/s maximum drift rate
- relative phases of modulation chosen randomly over [0,2*pi] on initialization
- Actual modulation amplitude chosen randomly over [45 ppm, 50 ppm]

Cases 1 - 3: accumulate neighborRateRatio
Cases 4 - 6: measure GM rate ratio using successive Sync msgs



Revised Results for dTE_R for Previous Cases (1 - 8) - 9

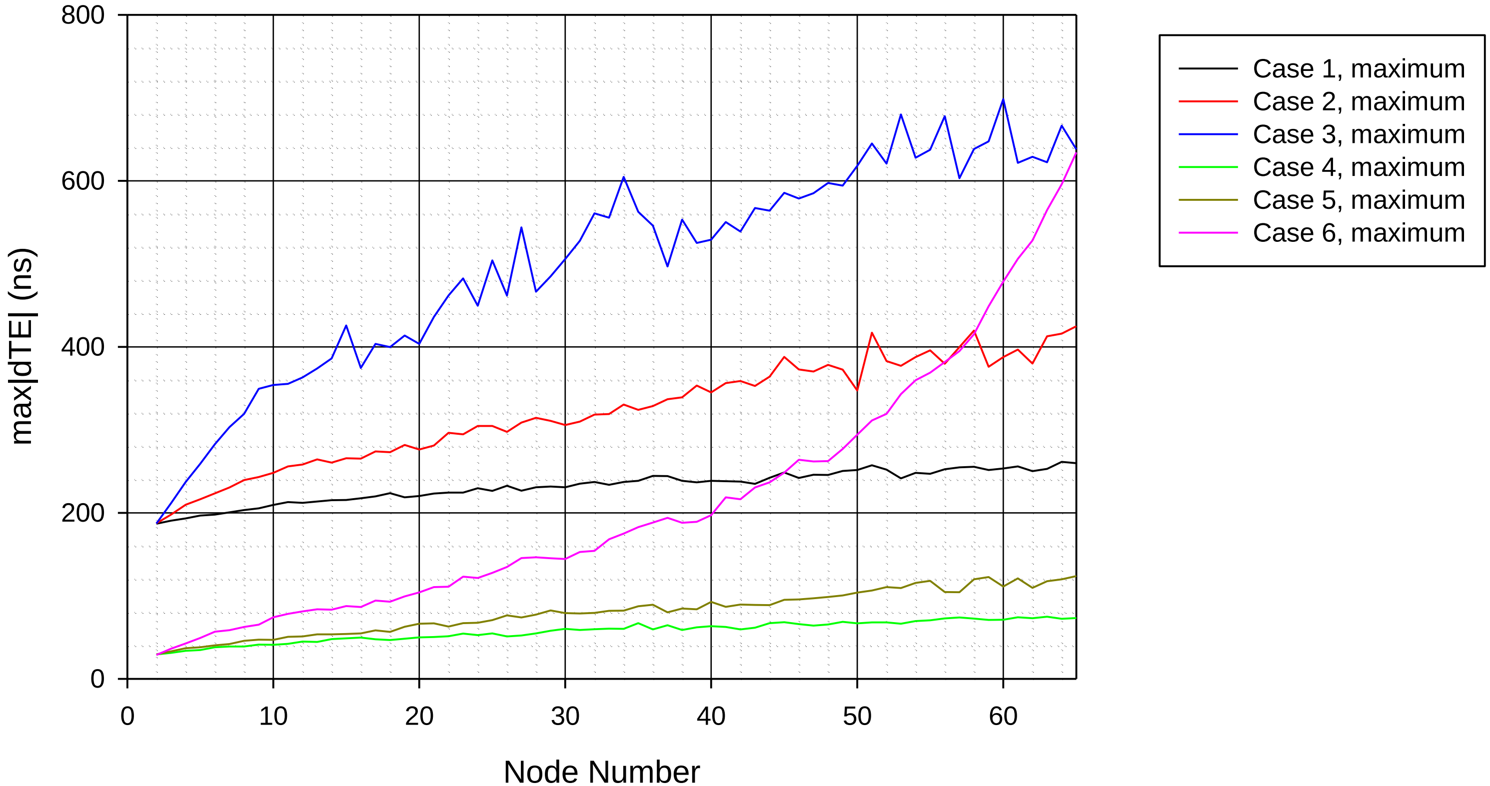
Simulation Cases 1 - 6
300 replications of simulation
Clock Model: sinusoidal phase and freqeuncy variation
    50 ppm max freq offset
    3 ppm/s maximum drift rate
    relative phases of modulation chosen randomly over [0,2*pi] on initialization
    Actual modulation amplitude chosen randomly over [45 ppm, 50 ppm]
Cases 1 - 3: accumulate neighborRateRatio
Cases 4 - 6: measure GM rate ratio using successive Sync msgs



Results for dTE, Zero Error in GM Time Source (previous results, from [2]) - 10

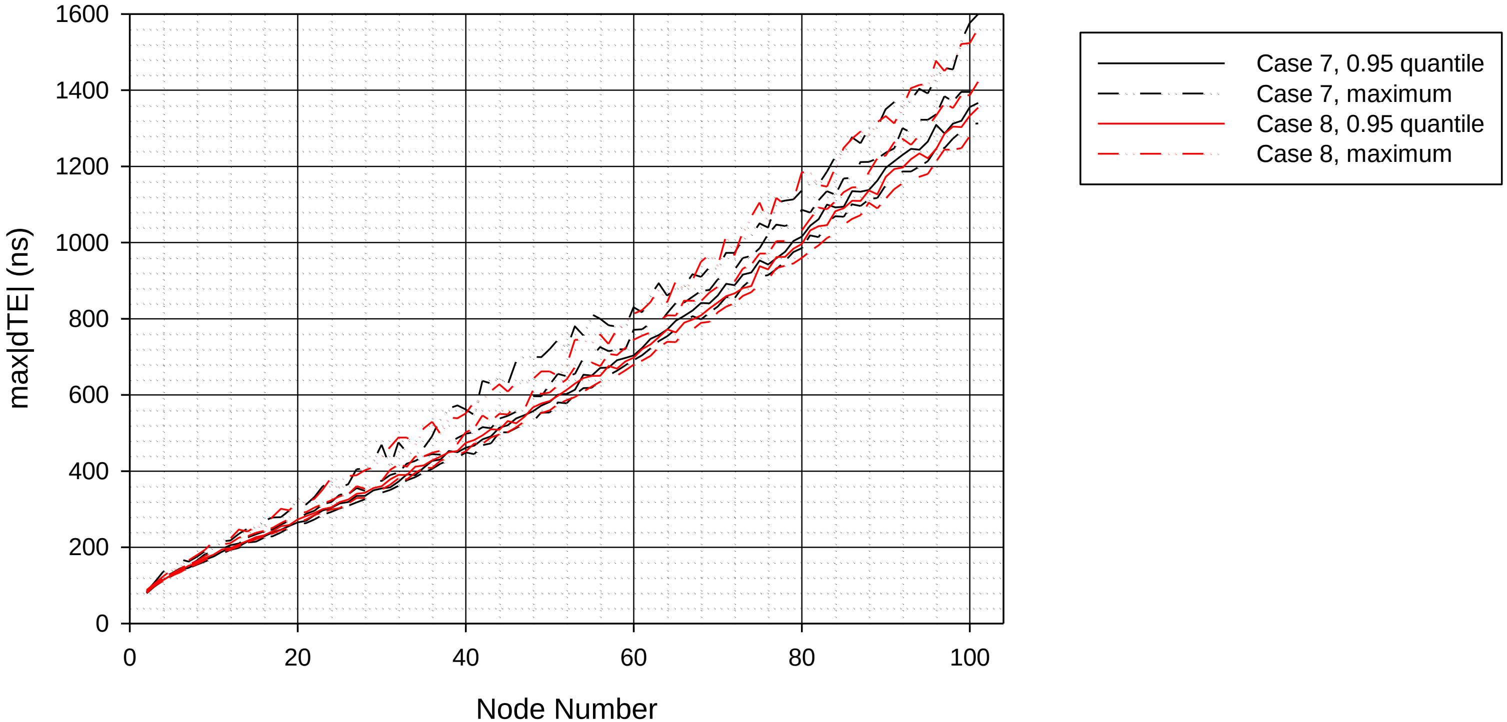
Simulation Cases 1 - 6
300 replications of simulation
Clock Model: sinusoidal phase and freqeuncy variation
- 50 ppm max freq offset
- 3 ppm/s maximum drift rate
- relative phases of modulation chosen randomly over [0,2*pi] on initialization
- Actual modulation amplitude chosen randomly over [45 ppm, 50 ppm]

Cases 1 - 3: accumulate neighborRateRatio
Cases 4 - 6: measure GM rate ratio using successive Sync msgs



Revised Results for dTE_R for Previous Cases (1 - 8) - 11

Simulation Cases 7 - 8
300 replications of simulation
Upper and lower 99% confidence intervals shown via short dashed lines
Clock Model: sinusoidal phase and freqeuncy variation
  50 ppm max freq offset
  3 ppm/s max drift rate
  relative phases of modulation chosen randomly over [0,2*pi] on init
  Actual modulation amplitude chosen randomly over [45 ppm, 50 ppm]
Accumulate neighborRateRatio
Endpoint filter: KiKo = 65, KpKo = 11
Resid time = 10 ms, Pdelay turn time = 1ms (case7),4ms (case8)

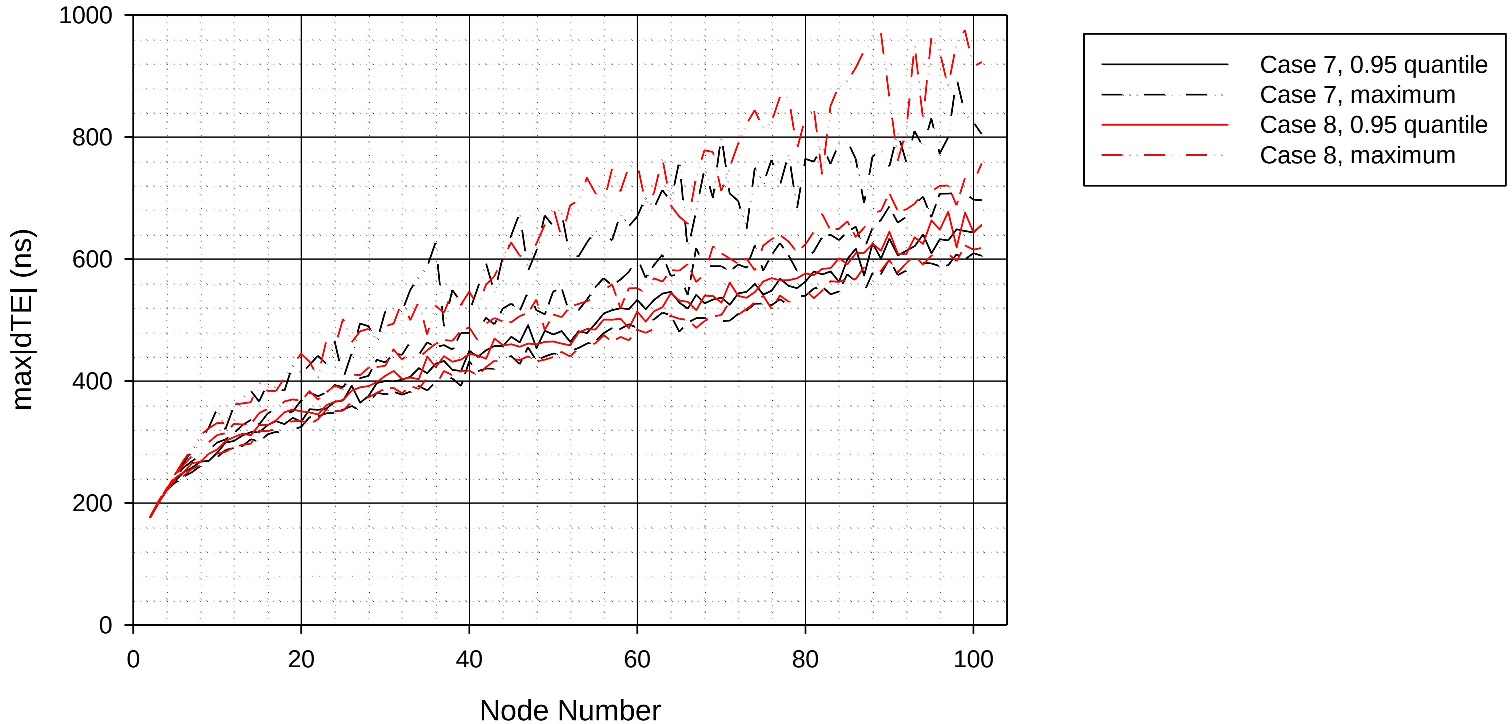


Results for dTE_R, Zero Error in GM Time Source (previous results, from [2]) - 12

Simulation Cases 7 - 8
300 replications of simulation
Upper and lower 99% confidence intervals shown via short dashed lines
Clock Model: sinusoidal phase and freqeuncy variation

- 50 ppm max freq offset
- 3 ppm/s max drift rate
- relative phases of modulation chosen randomly over [0,2*pi] on init
- Actual modulation amplitude chosen randomly over [45 ppm, 50 ppm]

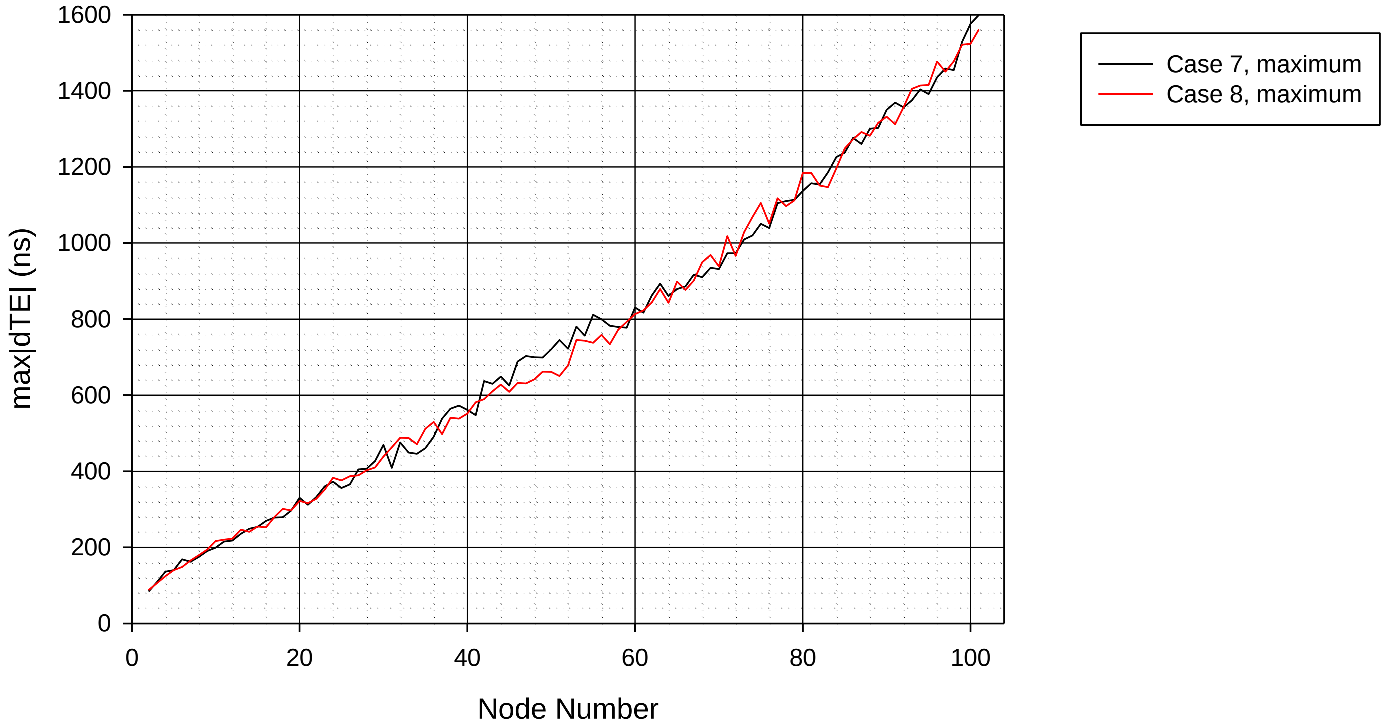
Accumulate neighborRateRatio
Endpoint filter: KiKo = 65, KpKo = 11
Resid time = 10 ms, Pdelay turn time = 1ms (case7),4ms (case8)



Revised Results for dTE_R for Previous Cases (1 - 8) - 13

Simulation Cases 7 - 8
300 replications of simulation
Upper and lower 99% confidence intervals shown via short dashed lines
Clock Model: sinusoidal phase and freqeuncy variation
- 50 ppm max freq offset
- 3 ppm/s max drift rate
- relative phases of modulation chosen randomly over [0,2*pi] on init
- Actual modulation amplitude chosen randomly over [45 ppm, 50 ppm]

Accumulate neighborRateRatio
Endpoint filter: KiKo = 65, KpKo = 11
Resid time = 10 ms, Pdelay turn time = 1ms (case7),4ms (case8)

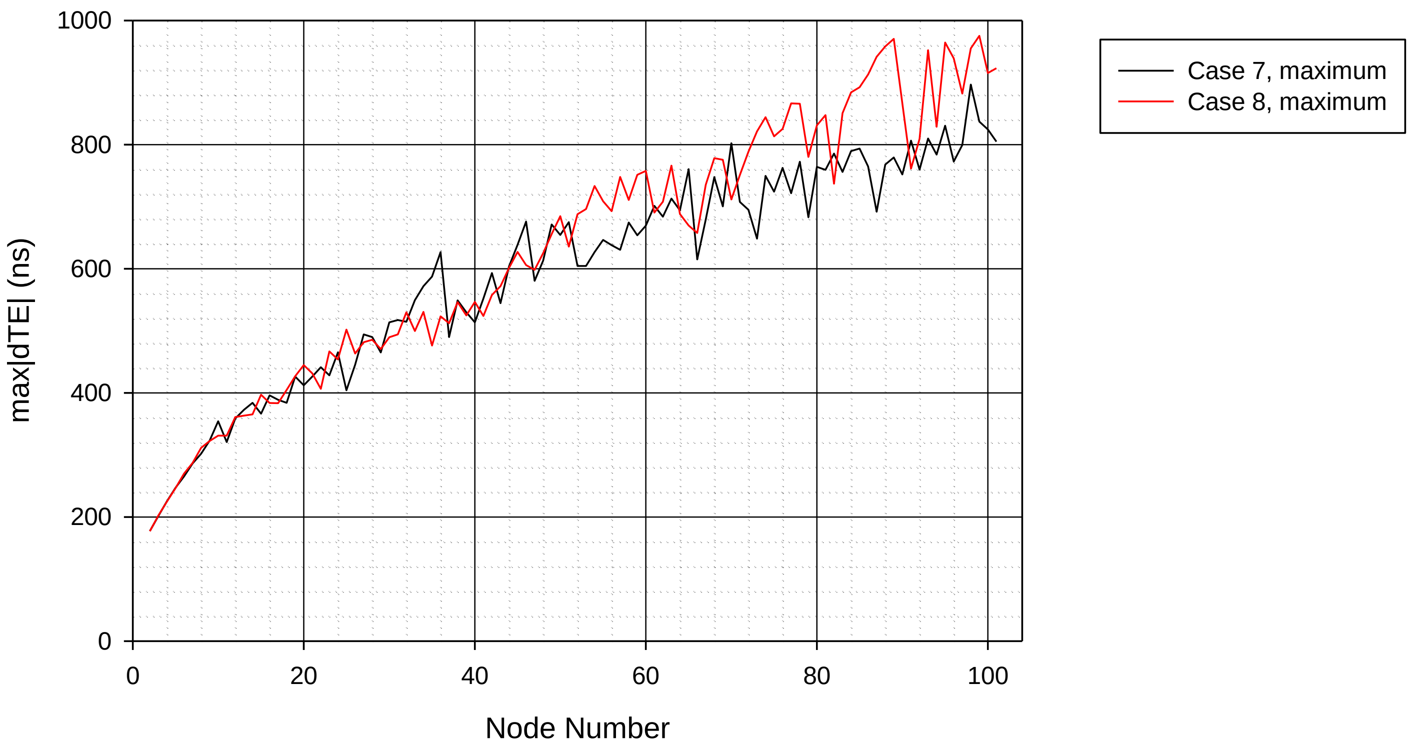


Results for dTE_R, Zero Error in GM Time Source (previous results, from [2]) - 14

Simulation Cases 7 - 8
300 replications of simulation
Upper and lower 99% confidence intervals shown via short dashed lines
Clock Model: sinusoidal phase and freqeuncy variation

- 50 ppm max freq offset
- 3 ppm/s max drift rate
- relative phases of modulation chosen randomly over [0,2*pi] on init
- Actual modulation amplitude chosen randomly over [45 ppm, 50 ppm]

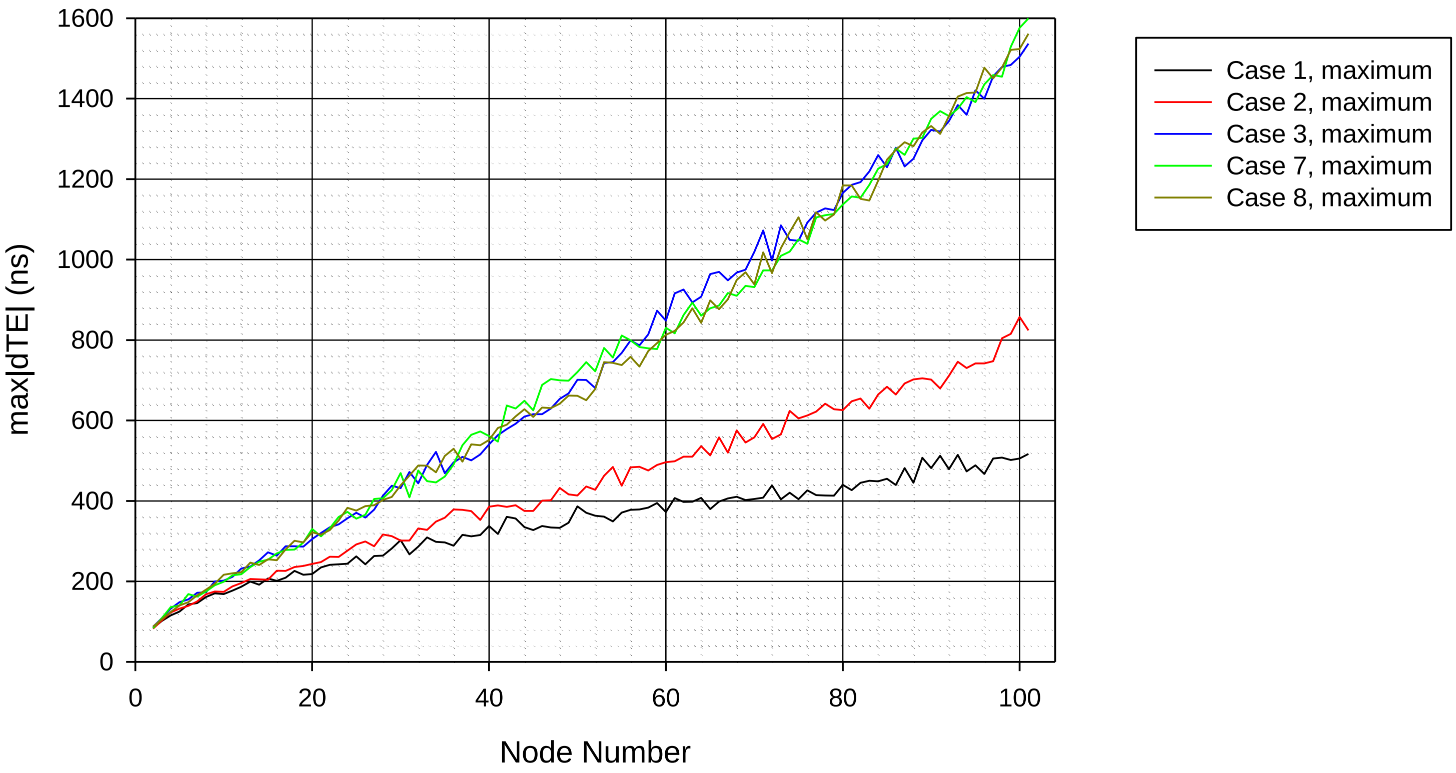
Accumulate neighborRateRatio
Endpoint filter: KiKo = 65, KpKo = 11
Resid time = 10 ms, Pdelay turn time = 1ms (case7),4ms (case8)



Revised Results for dTE_R for Previous Cases (1 - 8) - 15

Simulation Cases 1, 2, 3, 7, 8
300 replications of simulation
Clock Model: sinusoidal phase and freqeuncy variation
- 50 ppm max freq offset
- 3 ppm/s maximum drift rate
- relative phases of modulation chosen randomly over [0,2*pi] on initialization
- Actual modulation amplitude chosen randomly over [45 ppm, 50 ppm]

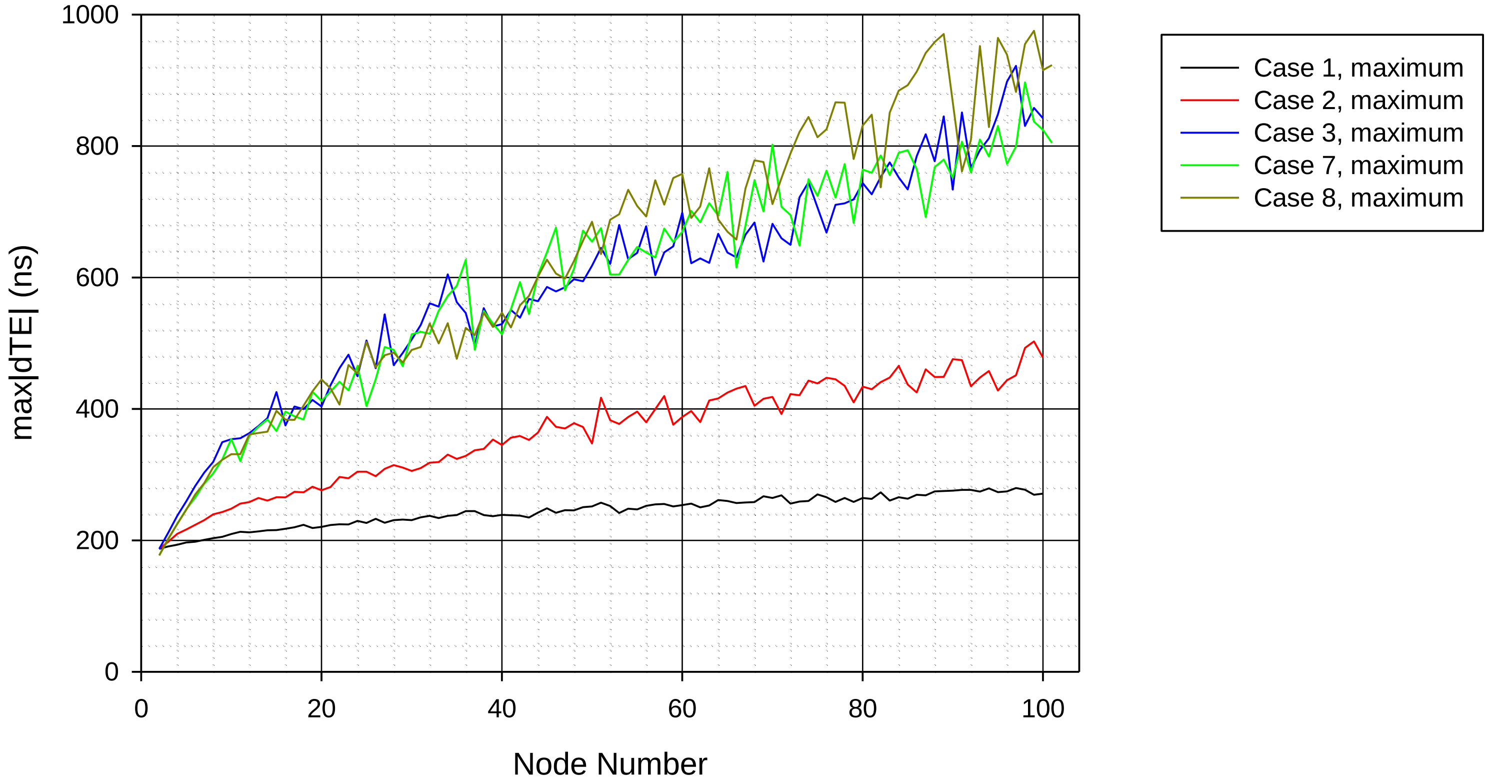
accumulate neighborRateRatio
Endpoint filter: KiKo = 249 (cases 1-3), 65 (cases 7-8)



Results for dTE, Zero Error in GM Time Source (previous results, from [2]) - 16

Simulation Cases 1, 2, 3, 7, 8
300 replications of simulation
Clock Model: sinusoidal phase and freqeuncy variation
- 50 ppm max freq offset
- 3 ppm/s maximum drift rate
- relative phases of modulation chosen randomly over [0,2*pi] on initialization
- Actual modulation amplitude chosen randomly over [45 ppm, 50 ppm]

accumulate neighborRateRatio
Endpoint filter: KiKo = 249 (cases 1-3), 65 (cases 7-8)



Revised Results for dTE_R for Previous Cases (1 - 8) - 17

- The new (i.e., revised) results for cases 1 – 8 are summarized in the table on the next slide (rounded to 2 or 3 significant digits), and compared with the results obtained in [1] and [2]
- The 50 ns error due to dynamic error of the GM, which was added to the previous results ([1] and [2]) has been subtracted, because it is not included in the new results
  - As indicated in the introduction, an improved analysis of this error is contained in the companion presentation [11]
- The new results are considerably larger than the previous results
  - This is mainly due to the $\pm$ 8 ns dynamic timestamp error for event messages due to variable delays within the PHY being included properly in the new simulations
- The 1 μs objective for $\max|TE_R|$ can likely be met for cases 1 and 4 (but not 2 and 5, as for the previous simulations) for 100 nodes, and for cases 1, 2, 4, and 5 for 65 nodes
- For other cases, either the 1 μs objective is exceeded, or it is met but with insufficient margin for other error budget components (i.e., cTE and effect of GM dynamic time error)
- As for the previous results, the results for cases 7 and 8 are similar to the results for case 3 (i.e., the smaller Pdelay turnaround time has small effect)

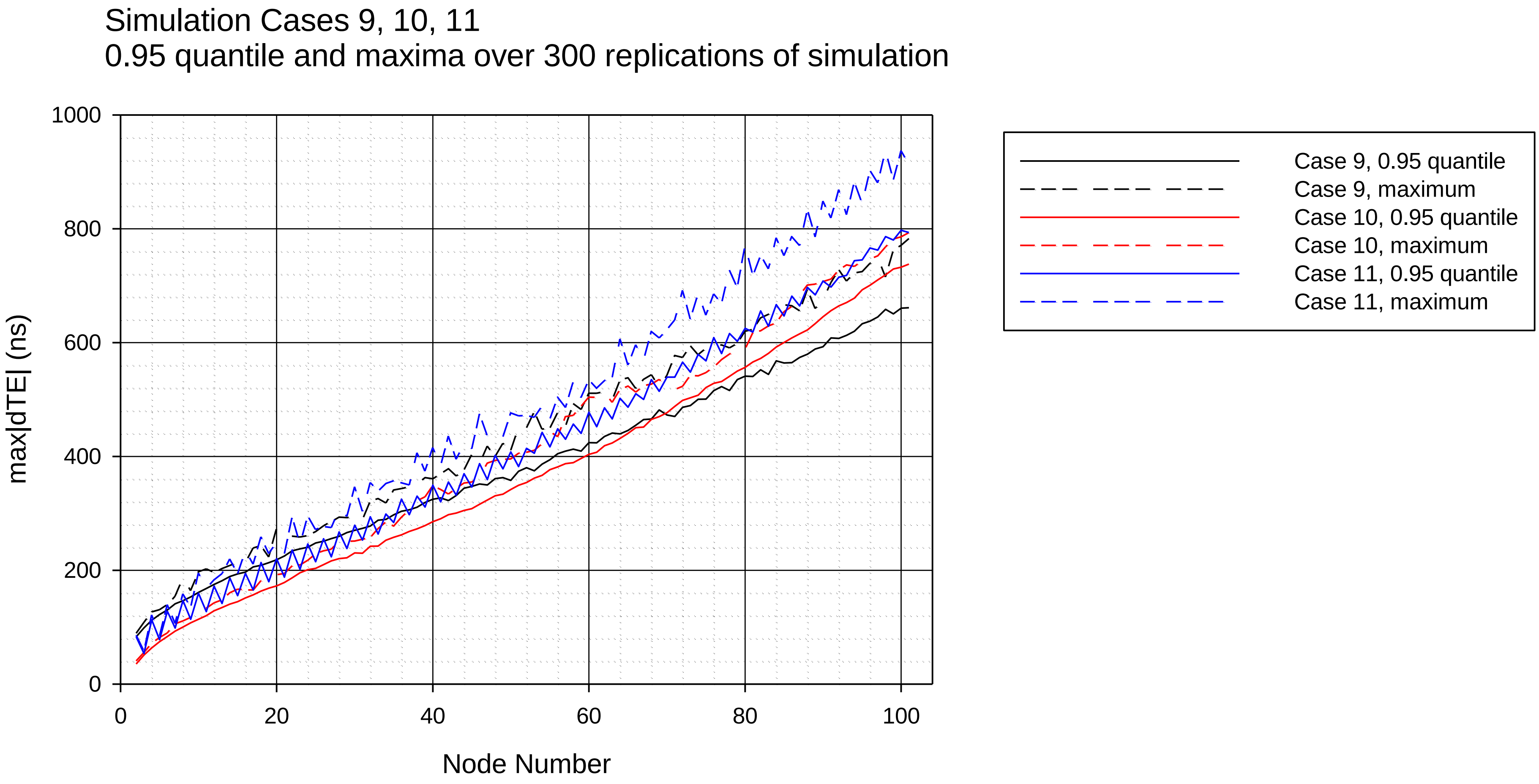
Revised Results for dTE_R for Previous Cases (1 - 8) - 18

Case	Syntonization Method and mean message intervals (ms)	Residence time (ms)	Pdelay turn-around time (ms)	Max|dTE_R|, 100 nodes (ns) Prev/revised	Max|dTE_R|, 65 nodes (ns) Prev/revised
1	Accumulate neighborRateRatio Mean Sync Interval = 125, Mean Pdelay Interval = 31.25	1	1	300 / 520	250 / 380
2		4	4	500 / 820	420 / 510
3		10	10	850 / 1540	680 / 960
4	Use successive Sync messages Mean Sync Interval = 31.25, Mean Pdelay Interval = 1000	1	10	100 / 580	40 / 480
5		4	10	200 / 1140	80 / 670
6		10	10	5700 / 18800	630 / 1940
7	Accumulate neighborRateRatio Mean Sync Interval = 125, Mean Pdelay Interval = 31.25	10	1	810 / 1600	760 / 880
8		10	4	920 / 1560	670 / 900

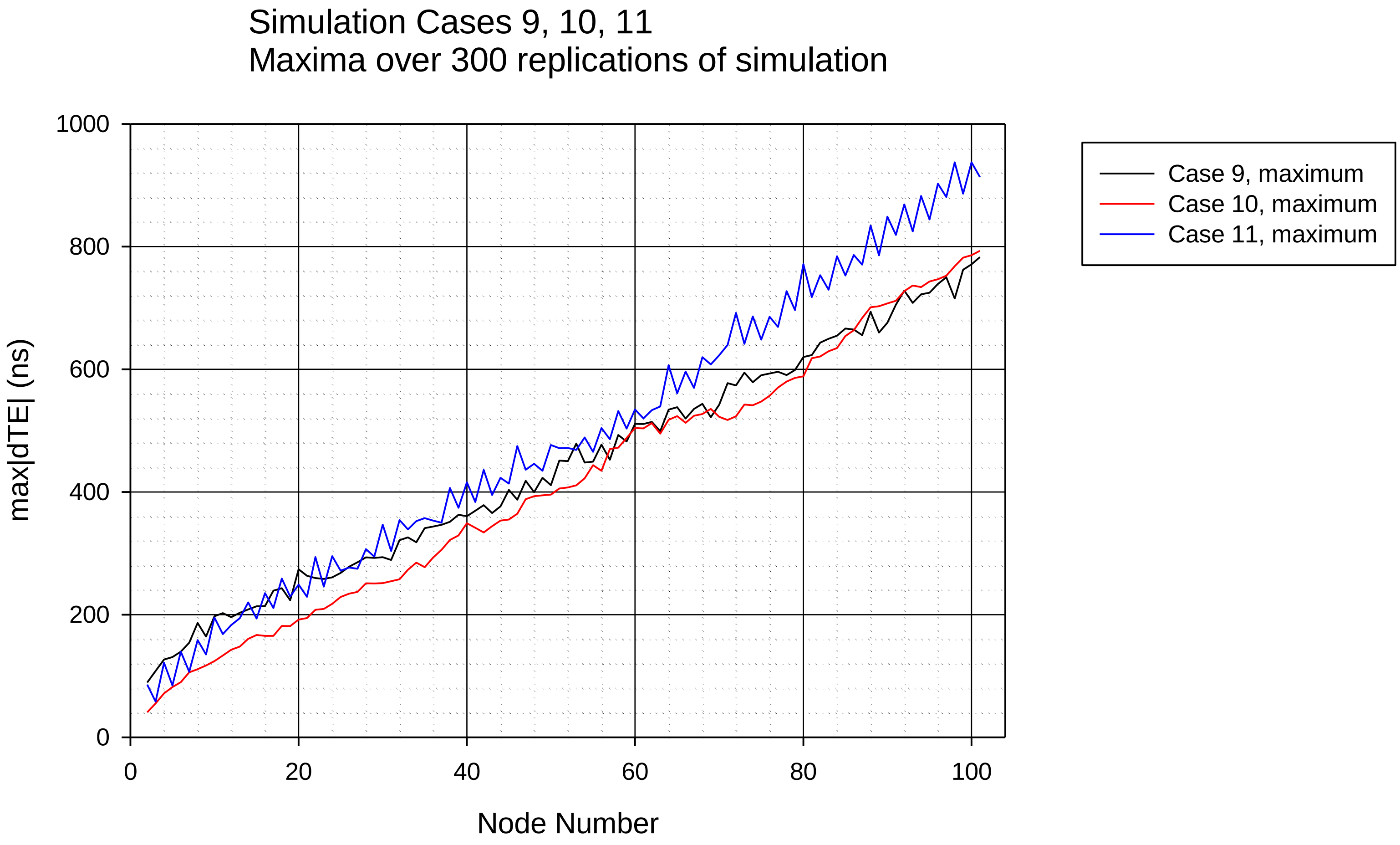
Results for dTE_R (Cases 9 - 11) - 1

- The following plots show results for cases 9 – 11
  - Max|dTE_R|, cases 9 – 11, nodes 2 – 100, 99% confidence intervals for 0.95 quantile, and maximum over 300 replications
  - Max| dTE_R |, cases 9 – 11, nodes 2 – 100, maximum over 300 replications (less cluttered than previous plot)
  - Max|dTE_R|, cases 9 – 811, nodes 2 – 65, 99% confidence intervals for 0.95 quantile, and maximum over 300 replications
  - Max| dTE_R |, cases 9 – 11, nodes 2 – 165, maximum over 300 replications (less cluttered than previous plot)

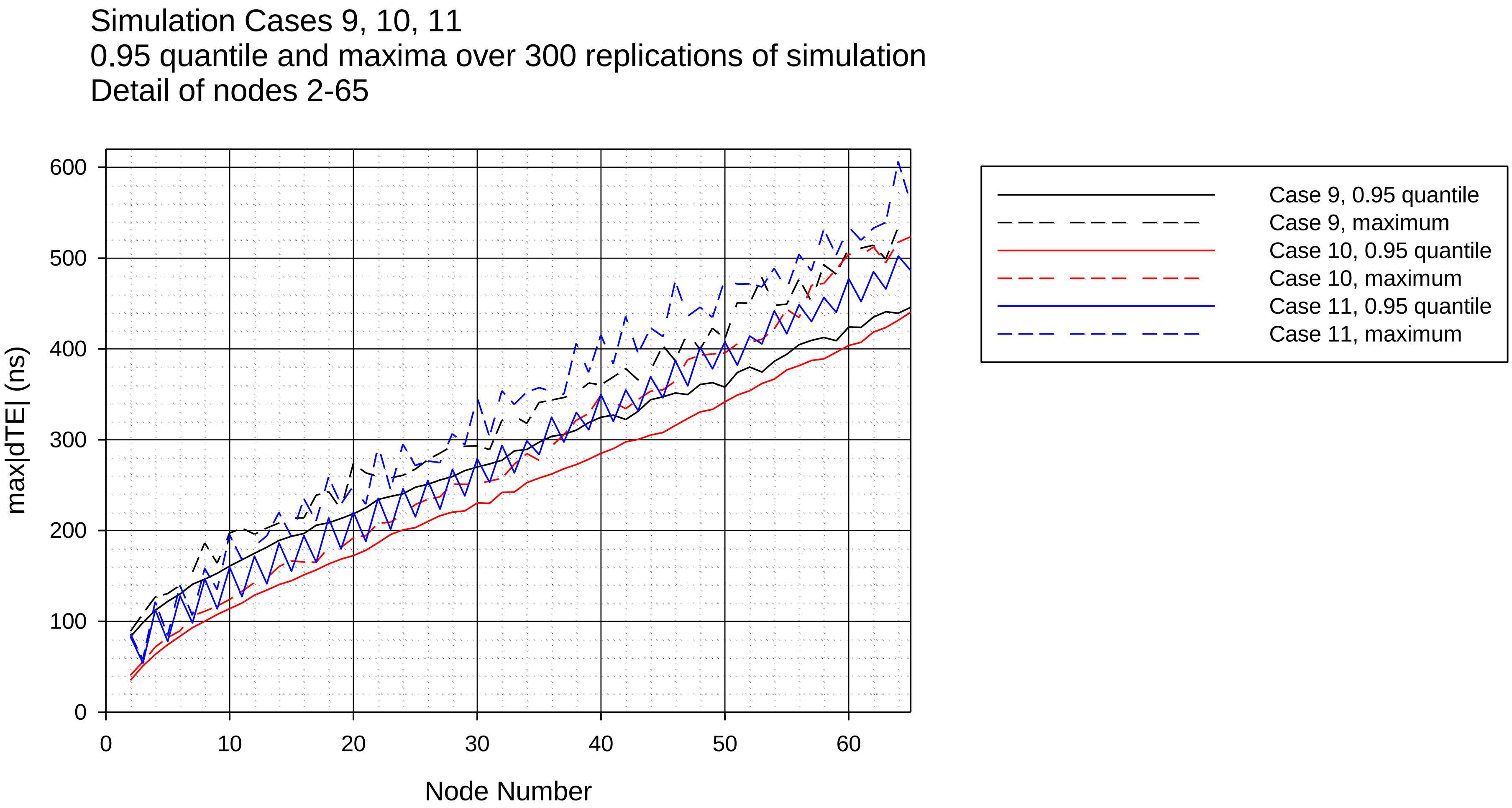
Results for dTE_R (Cases 9 - 11) - 2



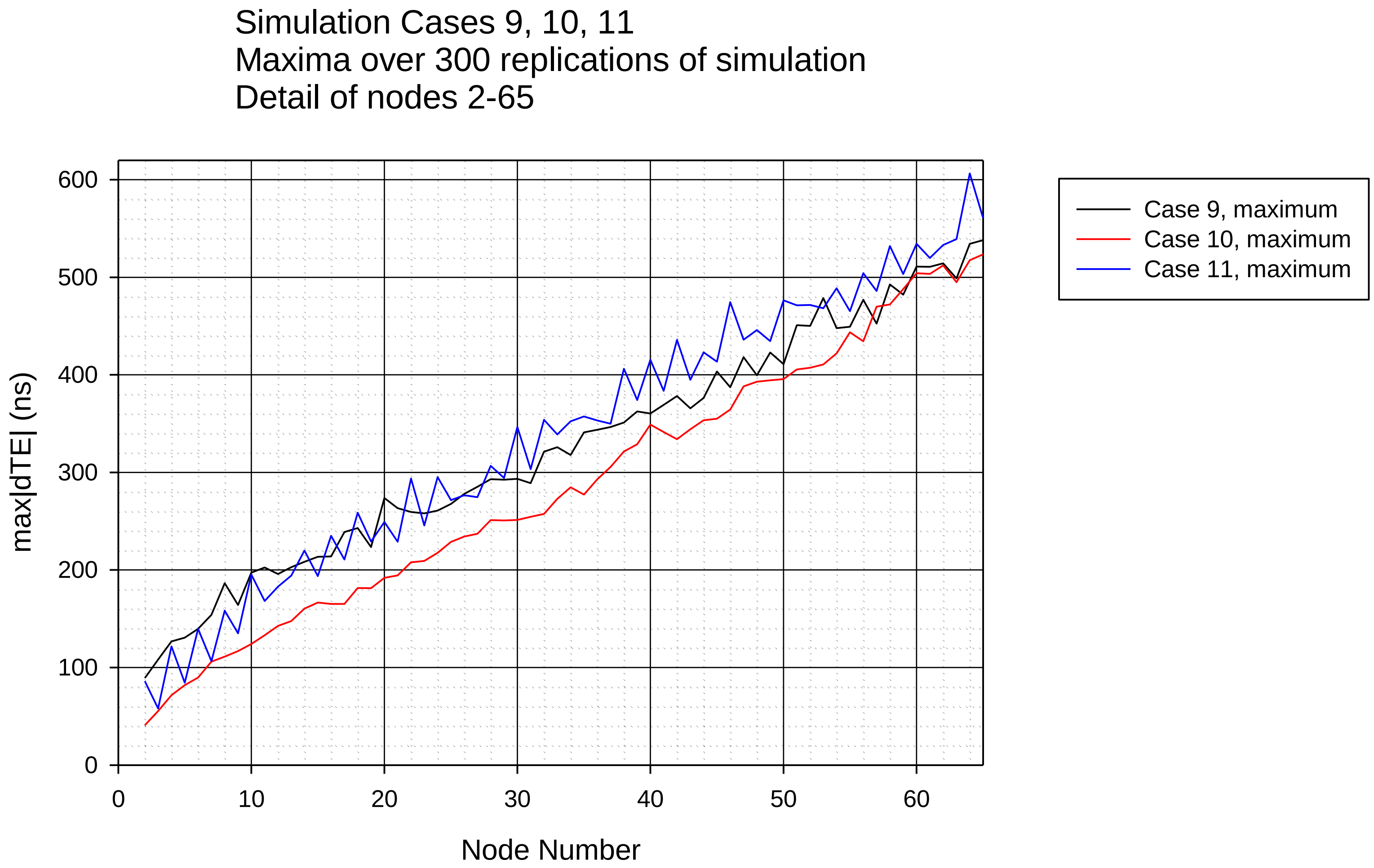
Results for dTE_R (Cases 9 - 11) - 3



Results for dTE_R (Cases 9 - 11) - 4



Results for dTE_R (Cases 9 - 11) - 5



Results for dTE_R (Cases 9 - 11) - 6

Case	Syntonization Method, mean message intervals (ms), and Pdelay turnaround time (ms)	Local clock maximum frequency drift rate (ppm/s)	Residence time (ms)	Max|dTE_R|, 100 nodes (ns)	Max|dTE_R|, 65 nodes (ns)
9	Accumulate neighborRateRatio Mean Sync Interval = 125, Mean Pdelay Interval = 31.25, Pdelay turnaround time = 10	3	4	783	538
10		0.3	10	793	524
11		3 and 0.3, alternating	4 and 10, alternating	913	561

- Results for cases 9 and 10 are similar, and also are similar to case 2 results
  - Case 2 has same parameters, except for Pdelay turnaround time, which is 4 ms instead of 10 ms for cases 9 and 10
- It appears that increasing the residence time to 10 ms and decreasing the maximum frequency drift rate to 0.3 ppm/s approximately compensate for each other, resulting in similar performance
- Case 11, which alternates the case 9 and 10 clock stability and residence time, gives slightly worse performance than either case 9 or case 10, but examining the performance for all 3 cases for nodes 2 – 101 indicates the difference could be due to statistical variability

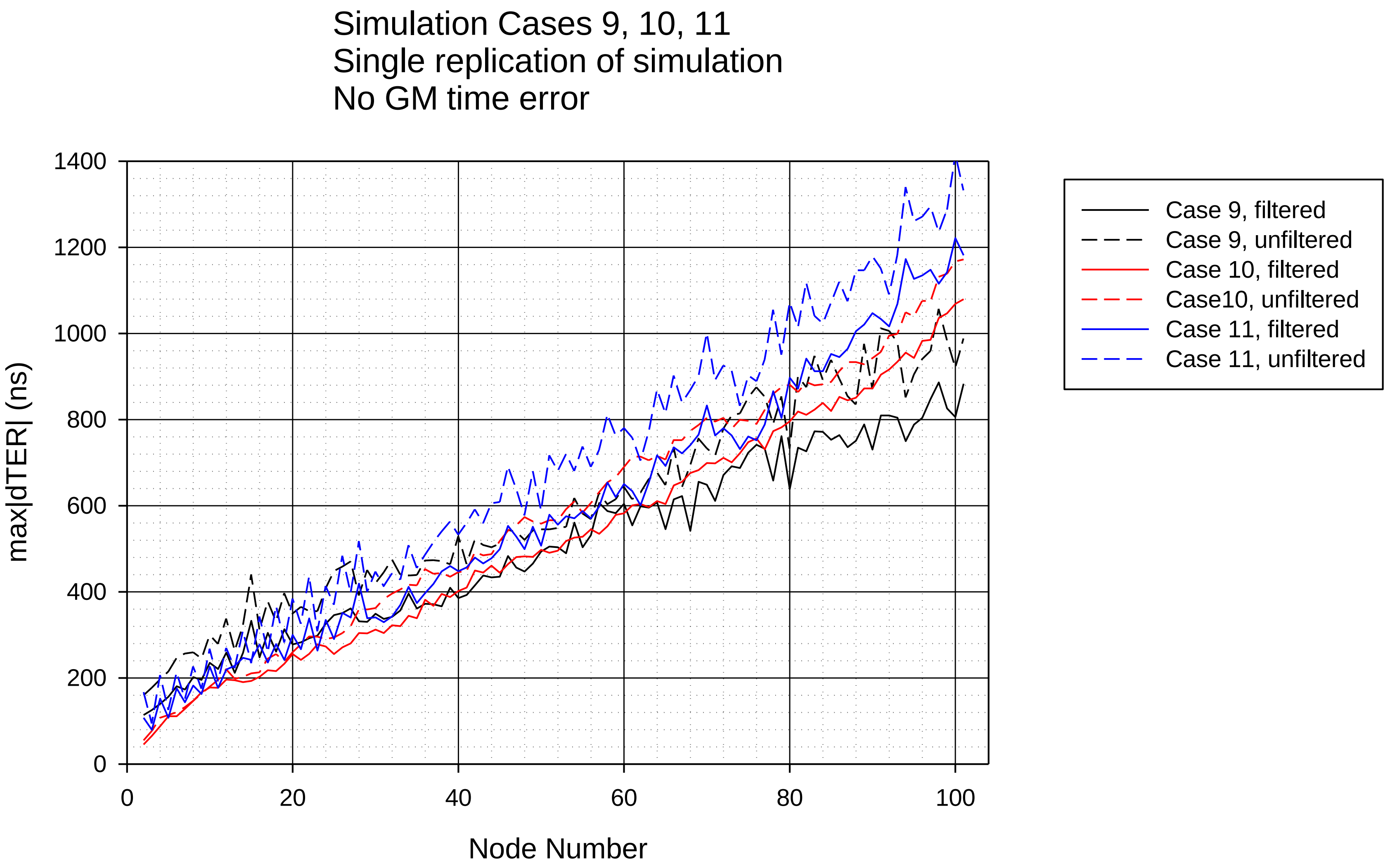
Results for dTE_R (Cases 9 - 11) - 7

- It appears that the 1 μs objective can be met over 65 nodes (64 hops), as approximately 400 – 500 ns margin remains for cTE and the effect of GM dynamic time error on $max|TE_R|$
- The effect of GM dynamic time error on $max|TE_R|$ is analyzed in [11]

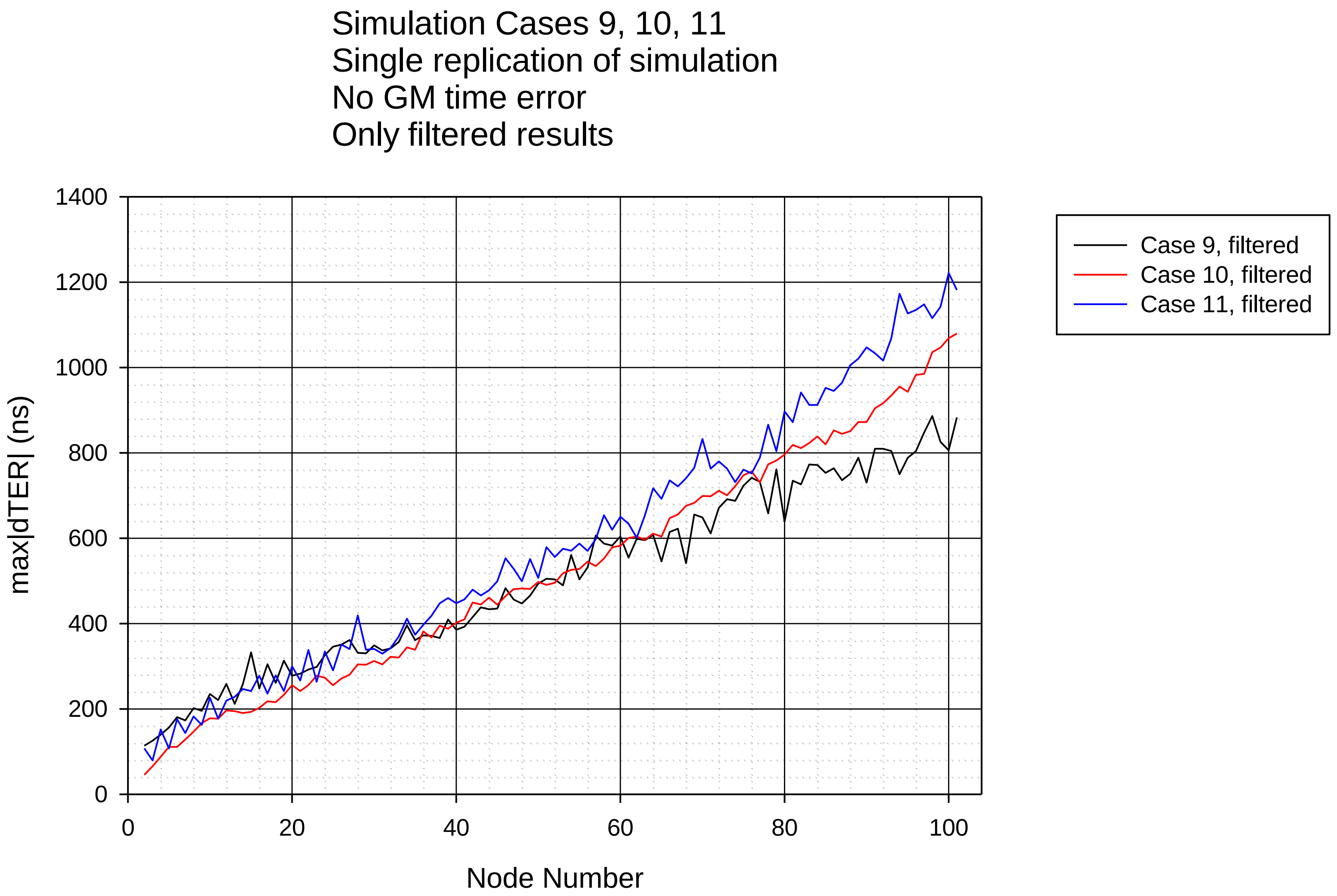
Revised results for cases 9 - 11, with corrected endpoint filter (with and without GM time error) - 1

- The following plots show revised results for cases 9 – 11 (no GM time error) and new results for cases 9 – 11 (with GM time error), nodes 2 – 101, all based on single replications of simulations
  - Max|dTE_R|, no GM time error, filtered and unfiltered results
  - Max| dTE_R |, no GM time error, only unfiltered results (so that plot will be less cluttered)
  - Max|dTE_R|, with GM time error, filtered and unfiltered results
  - Max| dTE_R |, with GM time error, only unfiltered results
- In addition, as a sanity check, Case 9 is simulated, but with zero timestamp error and timestamp granularity, and with the GM and all local clocks having the same frequency and phase
  - With these assumptions, neighborRateRatio is very close to 1, and the filtered result is very close to the result of filtering the GM time error with a high-pass filter whose bandwidth and damping ratio is the same as that of the endpoint filter (see slides 60 – 62 of [1])

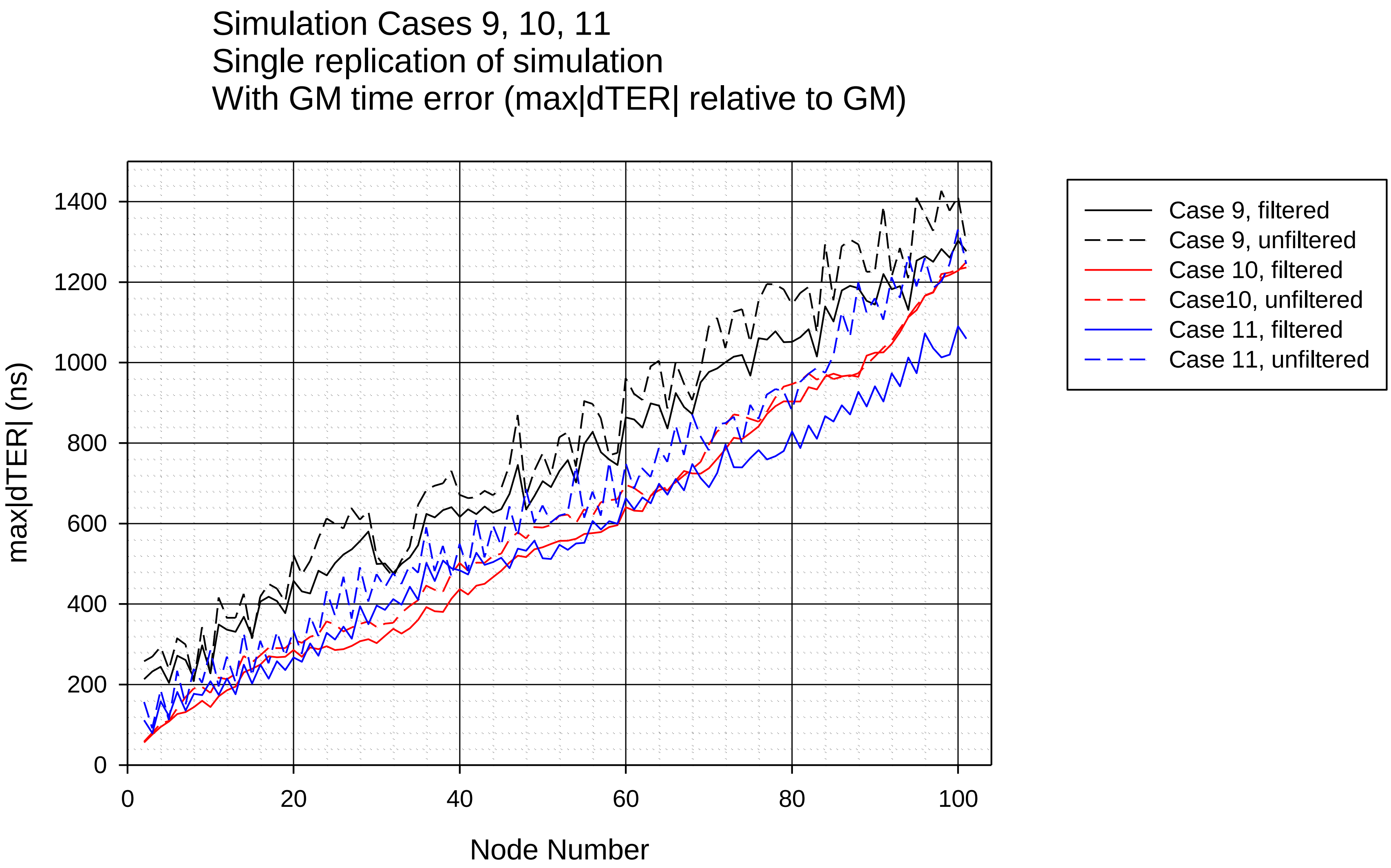
Revised Results for dTE_R (Cases 9 - 11), no GM time error - 2



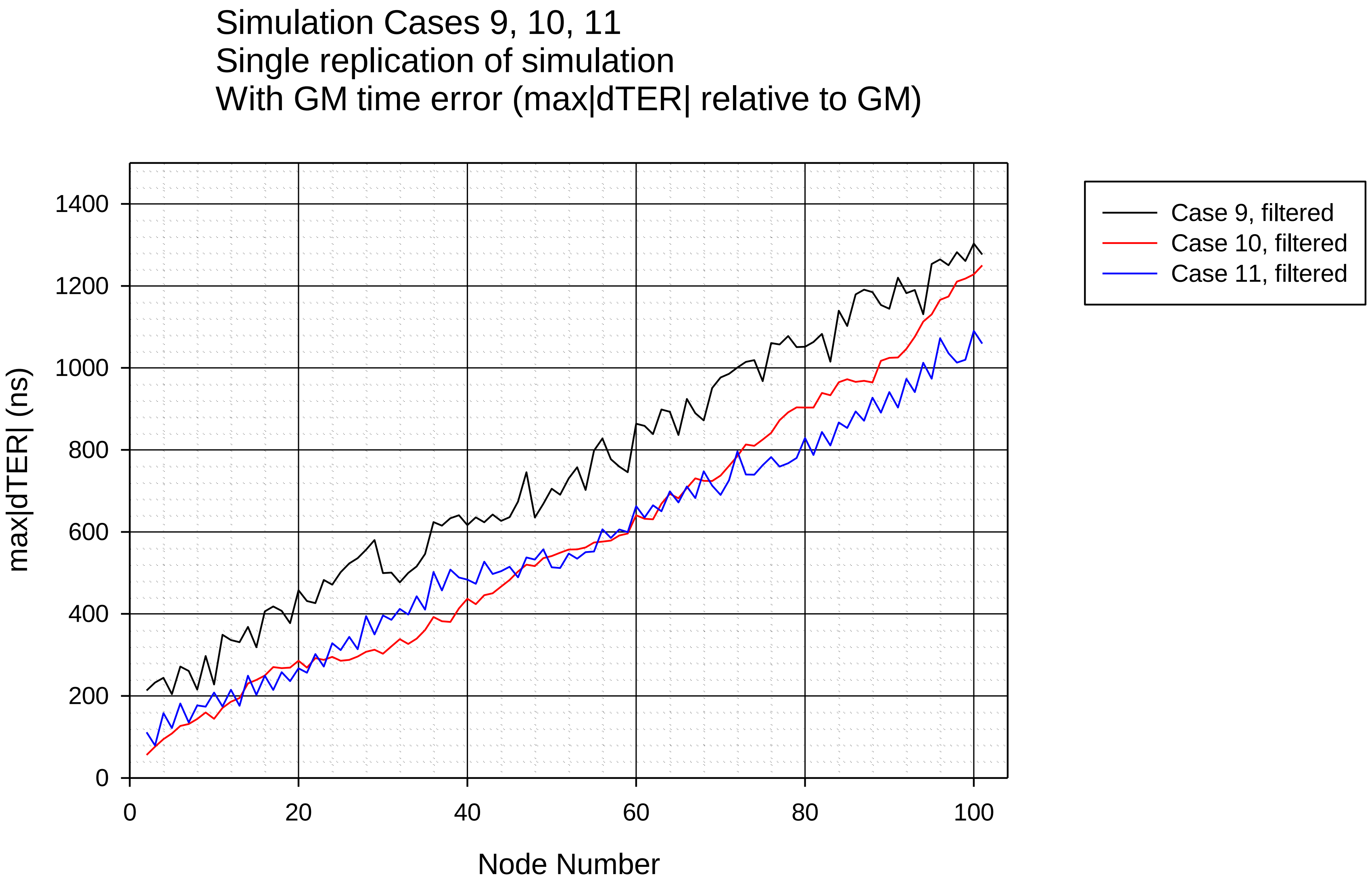
Revised Results for dTE_R (Cases 9 - 11), no GM time error, filtered results only - 3



Revised Results for dTE_R (Cases 9 - 11), with GM time error - 4



Revised Results for dTE_R (Cases 9 - 11), with GM time error, filtered results only - 5

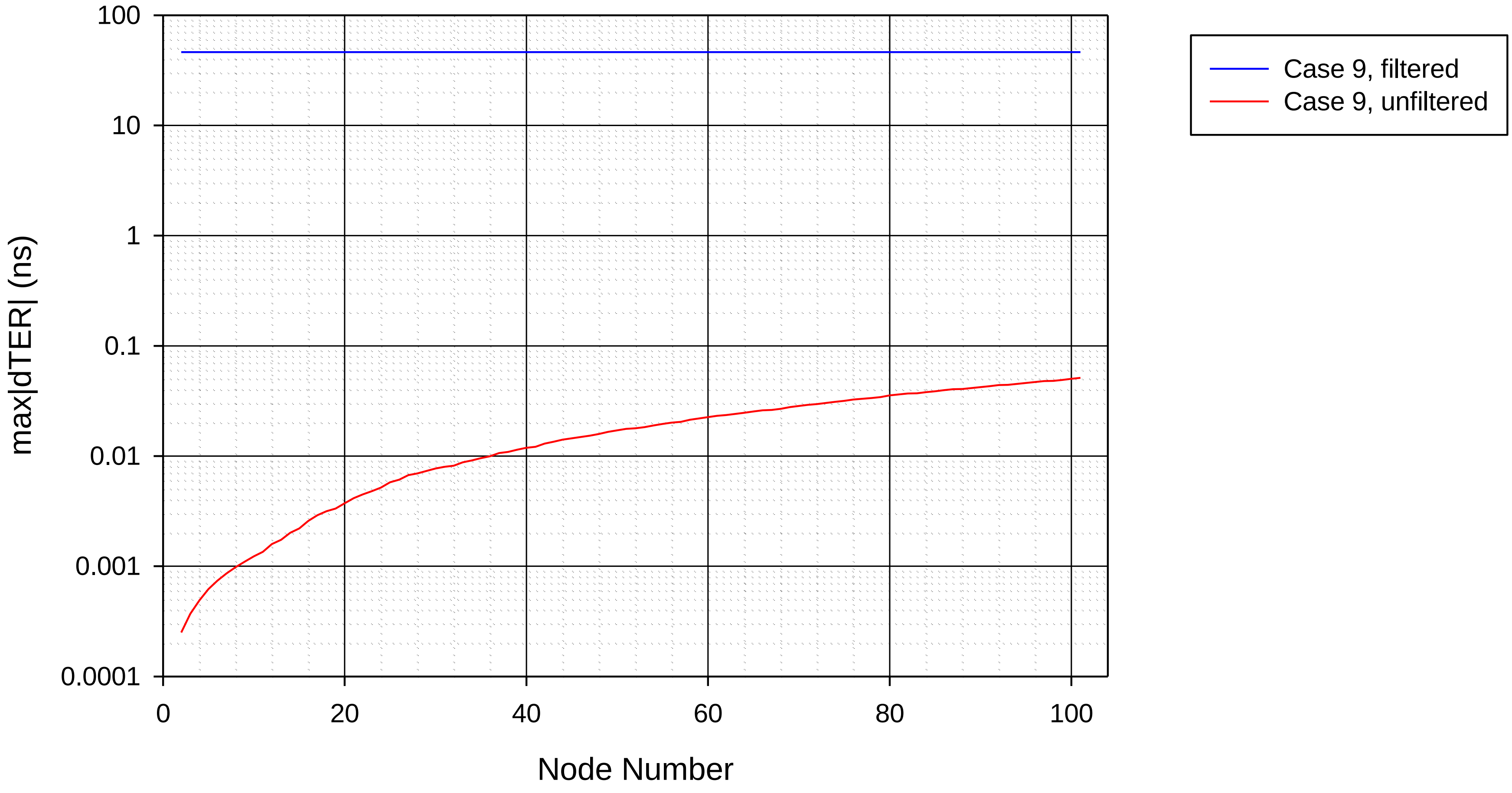


Revised Results for dTE_R (Cases 9 - 11), with GM time error, zero timestamp error and granularity, GM and all local clocks have same phase and frequency - 6

Simulation Cases 9, except with:

a) Timestamp granularity and timestamp error are zero

b) GM and all local clocks have same frequency and are in phase



Revised Results for dTE_R (Cases 9 - 11), with GM time error, zero timestamp error and granularity, GM and all local clocks have same phase and frequency - 7

- For the case of zero timestamp error, zero timestamp granularity, and the GM and all local clock frequencies and phases the same, neighborRateRatio is very close to 1.0 at each node (i.e., neighbor frequency offsets are zero)
- This means that the filtered output waveform is very close to the result of filtering the GM time
  - With these assumptions, neighborRateRatio is very close to 1, and the filtered dTE_R is very close to the result of filtering the GM time error with a high-pass filter whose bandwidth and damping ratio is the same as that of the endpoint filter (see slides 60 – 62 of [1])
  - For the GM time error assumptions used here and in [1], the resulting $\max|dTE_R|$ is very close to 46 ns (the results on the previous slide agree with the analytical calculation in [1])
  - In addition, the unfiltered $\max|dTE_R|$ is very close to zero, as indicated on the previous slide
    - The previous slide uses a log scale for $\max|dTE_R|$ so that the results can be seen more easily

Results for dTE_R (Cases 9 - 11), no GM time error - 7 (comparison with previous results) - 8

Case	Syntonization Method, mean message intervals (ms), and Pdelay turnaround time (ms)	Local clock maximum frequency drift rate (ppm/s)	Residence time (ms)	Max|dTE_R|, 101 nodes (ns) Prev/revised	Max|dTE_R|, 65 nodes (ns) Prev/revised
9	Accumulate neighborRateRatio Mean Sync Interval = 125, Mean Pdelay Interval = 31.25, Pdelay turnaround time = 10	3	4	783/840	538/600
10		0.3	10	793/1080	524/610
11		3 and 0.3, alternating	4 and 10, alternating	913/1220	561/720

- The revised results are for the corrected endpoint filter model
  - The revised results are larger than the previous results because the incorrect endpoint filter model had the same bandwidth and gain peaking, but 40 dB/decade roll-off instead of 20 dB/decade
  - The 40 dB/decade provided for more filtering
- Results for cases 9 and 10 are similar up to approximately 60 – 80 nodes, but then deviate
  - However, note that this is only for a single replication
  - To determine whether the observations on slide 47 still hold, multiple replications must be simulated

Results for dTE_R (Cases 9 - 11), comparison of cases with and without GM time error - 9

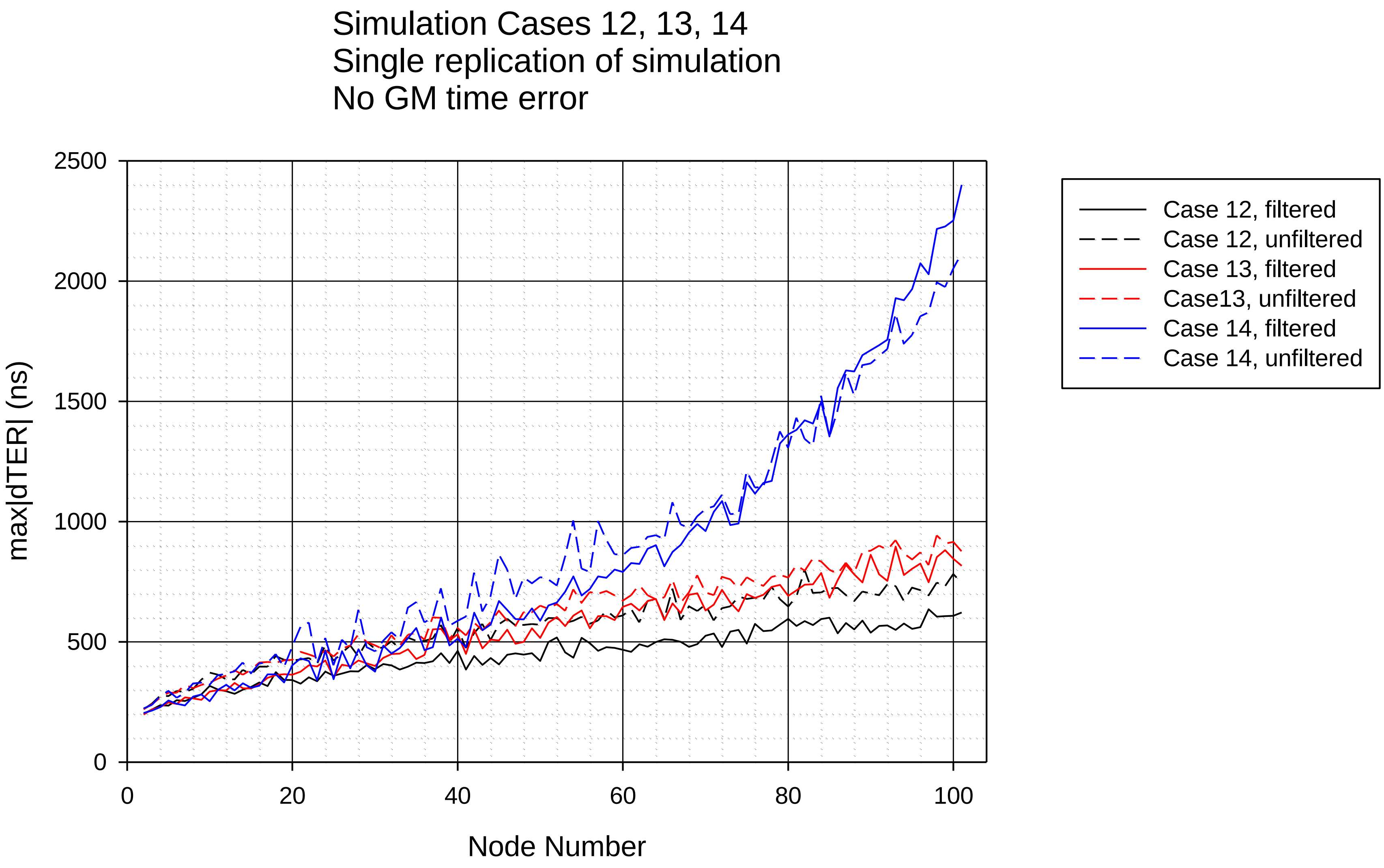
Case	Syntonization Method, mean message intervals (ms), and Pdelay turnaround time (ms)	Local clock maximum frequency drift rate (ppm/s)	Residence time (ms)	$\max\lvert dTE_R\rvert$, 101 nodes (ns) without/with GM time error	$\max\lvert dTE_R\rvert$, 65 nodes (ns) without/with GM time error
9	Accumulate neighborRateRatio Mean Sync Interval = 125, Mean Pdelay Interval = 31.25, Pdelay turnaround time = 10	3	4	840/1300	600/900
10		0.3	10	1080/1250	610/700
11		3 and 0.3, alternating	4 and 10, alternating	1220/1080	720/700

- All the results are for the corrected endpoint filter model
- Results for cases 9 and 10 are larger when GM time error is non-zero; however, results for case 11 are smaller
  - But, it is expected that results with GM time error would be larger; multiple replications must be run to determine if the case 11 results are due to statistical variability

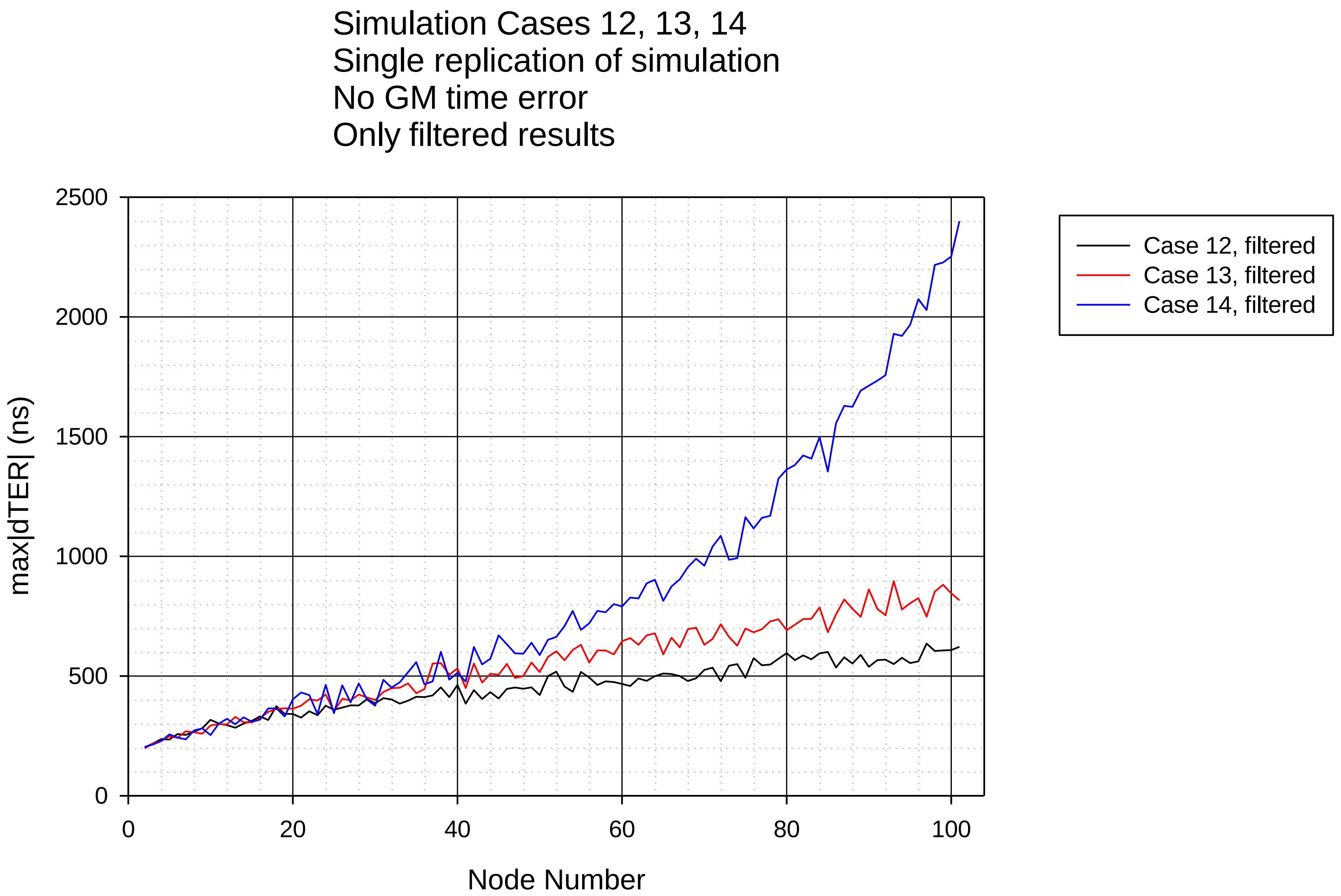
Results for cases 12 - 14, with corrected endpoint filter (with and without GM time error) - 1

- The following plots show revised results for cases 12 – 14, with and without GM time error, nodes 2 – 101, all based on single replications of simulations
  - Max|dTE_R|, no GM time error, filtered and unfiltered results
  - Max| dTE_R |, no GM time error, only unfiltered results (so that plot will be less cluttered)
  - Max|dTE_R|, with GM time error, filtered and unfiltered results
  - Max| dTE_R |, with GM time error, only unfiltered results

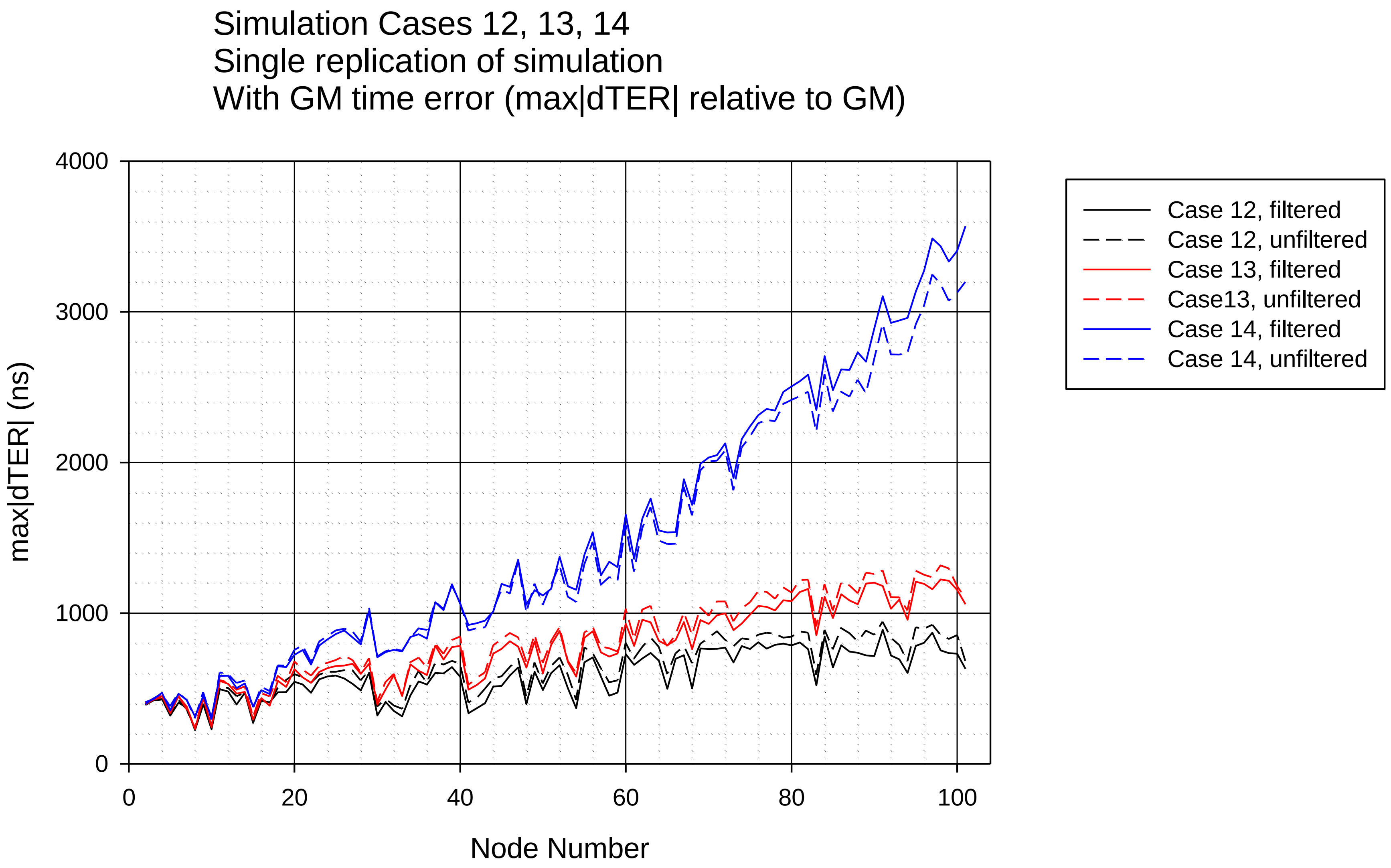
Results for cases 12 - 14, with corrected endpoint filter (no GM time error) - 2



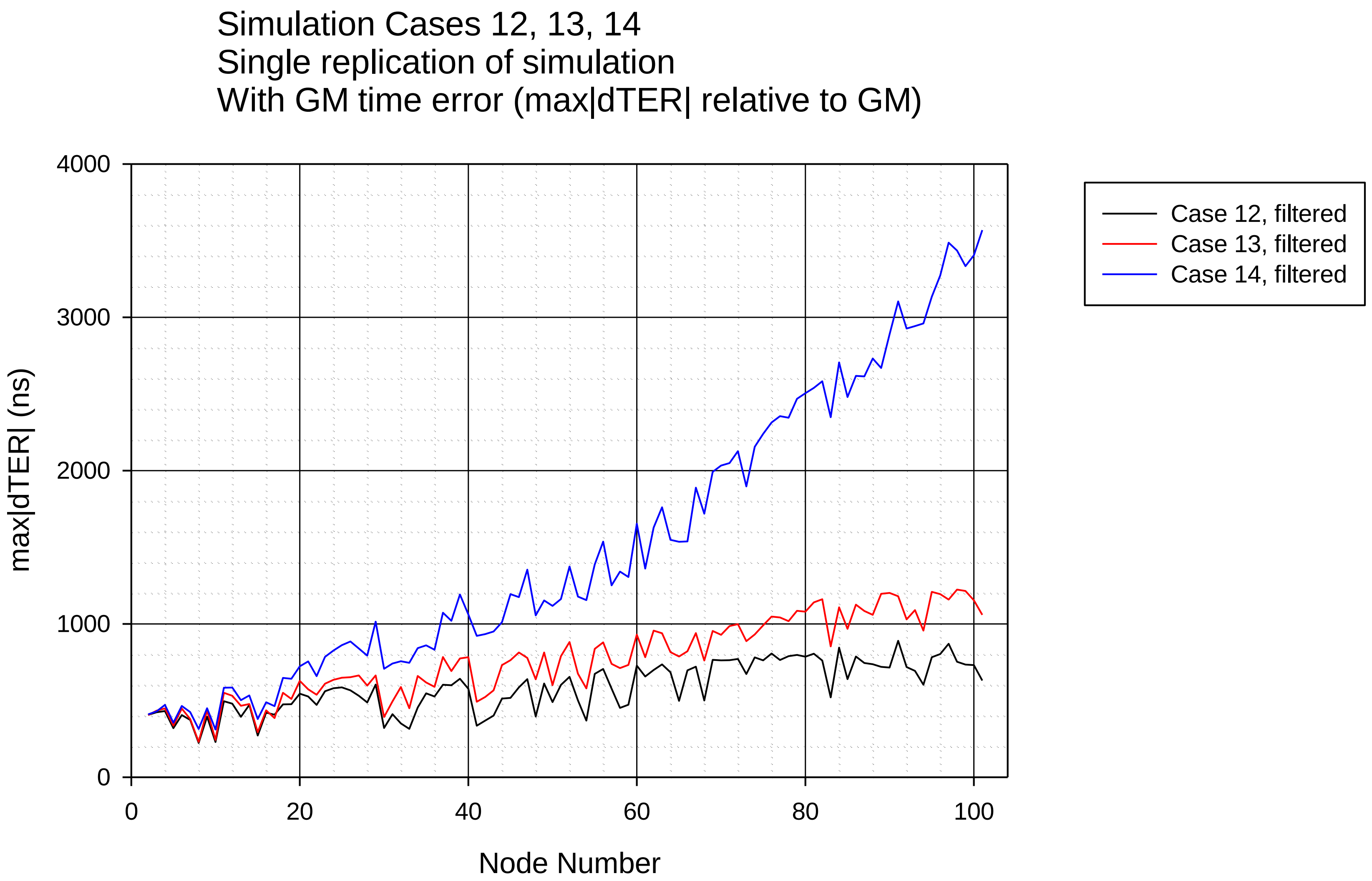
Results for cases 12 - 14, with corrected endpoint filter (no GM time error) - 3



Results for cases 12 - 14, with corrected endpoint filter (with GM time error) - 4



Results for cases 12 - 14, with corrected endpoint filter (with GM time error) - 5



Results for cases 12 - 14, with corrected endpoint filter (no GM time error), comparison with cases 4-6 - 6

Case	Syntonization Method and mean message intervals (ms)	Residence time (ms)	Pdelay turn-around time (ms)	Max|dTE_R|, 100 nodes (ns) Prev/revised	Max|dTE_R|, 65 nodes (ns) Prev/revised
4/12	Use successive Sync messages Mean Sync Interval = 31.25, Mean Pdelay Interval = 1000	1	10	580/620	480/500
5/13		4	10	1140/900	670/680
6/14		10	10	18800/2400	1940/900

Cases 11–14 differ from cases 4 – 6 in that (a) the window size for computation of GM rateRatio using successive Sync messages, and for the computation of neighborRateRation using successive Pdelay Messages, is increased from 7 previous messages (cases 4 – 6) to 11 previous messages (cases 11 – 14), and (b) The endpoint filter model is corrected (40 dB/decade for cases 4 – 6, versus 20 dB/decade for cases 11 – 14)

The larger window size seems to have small impact on cases 4 and 12, but its Impact is larger for larger residence time

Note that the exponential increase of accumulated time error with number of hops Is seen for the larger residence time (10 ms), as expected

Results for cases 12 - 14, with corrected endpoint filter (no GM time error), comparison of cases with and without GM time error - 6

Case	Syntonization Method and mean message intervals (ms)	Residence time (ms)	Pdelay turn-around time (ms)	Max|dTE_R|, 100 nodes (ns) without/with GM time error	Max|dTE_R|, 65 nodes (ns) without/with GM time error
12	Use successive Sync messages Mean Sync Interval = 31.25, Mean Pdelay Interval = 1000	1	10	620/880	500/750
13		4	10	900/1200	680/950
14		10	10	2400/3600	900/1750

In general, non-zero GM time error causes max|dTE_R| to increase, as expected.

Conclusion and Discussion of Next Steps

- The results for cases 9 – 11 indicate that the 1 μs objective for max|TE_R| can likely be met over 65 nodes (64 hops), though it must be checked whether there is sufficient margin for cTE and the effect of GM dynamic time error
- The results for cases 9 – 11 indicate that the 1 μs objective for max|TE_R| likely cannot be met over 101 nodes (65 hops)
- The new results for cases 1 – 8, based on revised analyses that properly account for the ± 8 ns dynamic timestamp error for event messages due to variable delays within the PHY are considerably larger than the previous results (in [1] and [2]) for these cases
- However, the main change to the conclusions of [2] is that, whereas the 1 μs objective for max|TE_R| could likely be met over 101 nodes for cases 1, 2, 4, and 5 for the results of [1] and [2], it is only met for cases 1 and 4 over 101 nodes for the new results
- There is no change to the conclusion for 65 nodes; the 1 μs objective for max|TE_R| is met for cases 1, 2, 4, and 5
- The effect of GM dynamic time error on max|TE_R| must also be considered
  - It is analyzed in [11]

Revised Conclusions and Next Steps - Revision2 - 1

- The revised and new results for cases 9 – 11 suggest that the 1 μs objective for max|TE| can be met over 65 nodes (64 hops) for cases 10 and 11, even if GM time error is nonzero; however, it must be checked whether there is sufficient margin for cTE and any other error budget components
  - However, case 9 appears to have insufficient margin for cTE (and any other error budget components)
- The revised an new results for cases 9 – 11 indicate that the 1 μs objective for max|TE| cannot be met over 101 nodes (100 hops), regardless of whether GM time error is zero or non-zero
  - The results for max|dTE_R| exceed 1 μs in every case except case 9 if GM time error is zero, but this case leaves insufficient margin for cTE and other budget components
- The new cases where successive Sync messages are used to measure GM rateRatio, for the case where GM time error is non-zero, either exceed 1 μs or are within 1 μs but leave insufficient margin for cTE and any other error budget components
  - The only possible exception to this is case 12 for 65 nodes (where max|dTE_R| is 750 ns for the case where GM time error is nonzero)

Revised Conclusions and Next Steps - Revision2 - 2

- All the new results are based on single replications of each simulation; multiple replications must be run to get better statistical confidence
- Multiple replications can be run
  - Should all the cases 9 – 14, with and without GM time error, be run, or only cases with GM time error?
  - Should any other simulation parameters/assumptions be changed?

Thank you

References - 1

[1] Geoffrey M. Garner, *New Simulation Results for Time Error Performance for Transport over an IEC/IEEE 60802 Network Based on Updated Assumptions*, IEEE 802.1 presentation, September 2020.

[2] Geoffrey M. Garner, *New Simulation Results for Time Error Performance for Transport over an IEC/IEEE 60802 Network Based on Updated Assumptions, Revision 3*, IEEE 802.1 presentation, October 2020.

[3] Geoffrey M. Garner, *Further Simulation Results for Time Error Performance for Transport over an IEC/IEEE 60802 Network*, Revision 1, IEEE 802.1 presentation, July 2020.

[4] Geoffrey M. Garner, *New Simulation Results for Time Error Performance for Transport over an IEC/IEEE 60802 Network*, Revision 1, IEEE 802.1 presentation, May 2020.

[5] Geoffrey M. Garner, *Initial Simulation Results for Time Error Accumulation in an IEC/IEEE 60802 Network*, IEEE 802.1 presentation, March 2020.

References - 2

[6] Geoffrey M. Garner, *Discussion of Assumptions Needed for 60802 Network Simulations*, IEEE 802.1 presentation, January 2020.

[7] Geoffrey M. Garner, *Comparison of 802.1AS Annex B and 60802 Clock Stability*, IEEE 802.1 presentation, January 2020.

[8] Guenter Steindl, *IEC/IEEE 60802 Synchronization requirements and solution examples*, IEEE 802.1 presentation, available at http://www.ieee802.org/1/files/public/docs2020/60802-Steindl-SynchronizationModels-0620-v1.pdf.

[9] Guenter Steindl, *IEC/IEEE 60802 Synchronization requirements and solution examples, Update after July 2020 plenary*, IEEE 802.1 presentation, July 30, 2020 available at https://www.ieee802.org/1/files/public/docs2020/60802-Steindl-SynchronizationModels-0720-v2.pdf

References - 3

[10] Geoffrey M. Garner, *Summary of Assumptions for Further Simulations of Time Error Performance for Transport over an IEC/IEEE 60802 Network*, IEEE 802.1 presentation, July 29, 2020, available at https://www.ieee802.org/1/files/public/docs2020/60802-garner-summary-of-assumptions-for-further-simulations-0720-v00.pdf.

[11] Geoffrey M. Garner, Improved Analysis of Component of dTE_R for Synchronization Transport over an IEC/IEEE 60802 Network due to GM Time Error , IEEE 802.1 presentation, November 2, 2020.