Further Analysis of cTE Budgeting for an IEC/IEEE 60802 Network, Based on Multiple Replication dTE simulations with Variable Inter-message Intervals

Revision 1

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Introduction - 1

- Reference [1] provided an initial analysis of budgeting for constant time error (cTE) in an IEC/IEEE 60802 network
- The analysis was based on the initial cTE accumulation analysis given in [2]
- The budgeting required results for max|dTE_R| accumulated over a network
- The latest max|dTE_R| results, contained in [3], were used (the subscript R denotes the time error relative to the GM)
- These results included the effect of variable duration message intervals for Sync and Pdelay messages
  - The dTE results also included the effect of time-varying GM error, measurement of neighborRateRatio using a window of Pdelay exchanges (window and computing the median, and other assumptions, all described in References [4], [5], and [6]
  - However, the results of [3] were based on single replications of dTE simulations, because multiple replication simulations would have required considerable run time (approximately 3 weeks per simulation case, with the possibility of running up to 4 cases simultaneously)
- It was realized that max|dTE_R| would be larger for multiple replications
  - The increase was estimated to be in the range 100 – 250 ns (for both 64 hops and 100 hops) by comparing single (replication 1, see [5]) and multiple replication (see [4]) results for previous simulations with fixed message intervals

Introduction - 2

- When the increase in $\max|dTE_R|$ due to running multiple replications was considered (the worst case of 250 ns was used), the resulting budgets for cTE were extremely stringent
- For a $\max|TE_R|$ objective of 1 μs, the resulting cTE budget was 134 ns for a 64-hop Hypothetical Reference Model (HRM) and 26 ns for a 100-hop HRM (or 100 ns for a 64-hop HRM based on less stringent assumptions)
- This resulted in cTE requirements of
  - 2.1 ns – 4.85 ns (per hop) for a 64-hop HRM
  - 0.26 ns – 0.75 ns (per hop) for a 100-hop HRM
  - 1 ns – 2.9 ns (per hop) for a 100-hop HRM, based on less stringent assumptions
- All these results for cTE assumed the worst case increase of 250 ns for $\max|dTE_R|$ when considering multiple replications of the simulations (compared to single replications)
- After discussion of [1], it was decided to perform multiple replications for one of the dTE simulation cases with variable message intervals, to see what the actual increase in $\max|dTE_R|$ is compared to single replication results
- The current presentation provides the new $\max|dTE_R|$ results and the effect on the cTE budgets and requirements

Introduction - 3

- The next 14 slides are taken from [1]
- These slides review the analysis of cTE accumulation

Review of Analysis of cTE Accumulation - 1

- Prior to the presentation of Reference [2] of [1], there were discussions of whether the accumulation of constant time error (cTE) should be linear or square-root-of-sum-of-squares (i.e., RMS)
- On the one hand, it was argued that if cTE is uniformly distributed, it is extremely unlikely that cTE will be at one extreme or another for all PTP instances and links in a hypothetical reference model (HRM)
  - With this argument, linear accumulation is overly conservative, and RMS accumulation should be used
- On the other hand, it was argued that, since cTE is fixed and constant, if a particular connection happens to have cTE at one extreme for all PTP Instances and links, it will remain this way permanently, or at least until the network is re-initialized
  - In the case where the cTE is permanently fixed, it is possible that cTE at most or all PTP Instances is similar and at one extreme if, for example, the same physical devices are used in most or all PTP Instances in the connection
  - With this argument, linear accumulation should be used

Review of Analysis of cTE Accumulation - 2

- Two types of cTE are considered:
  - cTE that is constant and permanently fixed
  - cTE that is constant and fixed for the duration of the interval that the network is up and operating, i.e., the cTE can change when the network is re-initialized
- Two HRM cases are considered (both are of interest for IEC/IEEE 60802 networks)
  - 100 hops
  - 64 hops
- Delay variation due to very long term effects, e.g., di-urnal temperature variation effects in links or aging of oscillators, is considered to be part of dTE and not considered here
  - Note that these effects were not considered in the analysis of [1] and previous analyses
  - The effect of aging is negligible compared to the effect of temperature, which was considered
  - The effect of di-urnal temperature variation in links was considered small for the link lengths of interest

Analysis of cTE Accumulation - 3

- There are three categories of cTE to consider

  1) cTE associated with the physical medium (i.e., link)
     - cTE in this category is fixed and constant for all time
     - Denote this by $x_{l,1}$
  2) cTE associated with the PTP Instance (i.e., node) that is fixed, and constant for all time
     - Denote this by $x_{n,2}$
  3) cTE associated with the PTP Instance (i.e., node) that is fixed while the node is up and operating, but changes when the node (or port if this cTE is associated only with the port) re-initializes
     - Denote this by $x_{n,3}$

- The category nomenclature is used here only for convenience; it is not standardized terminology, and can be replaced by other terminology if desired

Analysis of cTE Accumulation - 4

- For simplicity, assume all the above components of cTE have zero mean and are uniformly distributed
  1) $x_{l,1}$ is uniformly distributed over [- $D_{l,1}$, $D_{l,1}$]
  2) $x_{n,2}$ is uniformly distributed over [- $D_{n,2}$, $D_{n,2}$]
  3) $x_{n,3}$ is uniformly distributed over [- $D_{n,3}$, $D_{n,3}$]
- In saying that the cTE components are uniformly distributed, we mean
  - For components 1 and 2, a random cTE sample is permanently associated with each link and PTP Instance, respectively; this sample is taken from the respective uniform probability distribution
  - For component 3, a random cTE sample is taken from the respective uniform probability distribution whenever the PTP Instance is re-initialized, and this value (sample) is associated with that PTP Instance until the next time it is initialized

Analysis of cTE Accumulation - 5

- As indicated above, cTE has zero mean; the cTE probability density functions are

$$p_{x_k}(u) = \frac{1}{2D_k} \quad \text{for} \quad -D_k \le u \le D_k \quad \text{and} \quad k = l,1;\; n,2;\; n,3$$

- The variances of the cTE components are

$$\sigma_k^2 = \int_{-D_k}^{D_k} \frac{u^2}{2D_k}\, du = \frac{D_k^2}{3} \quad \text{for} \quad k = l,1;\; n,2;\; n,3$$

- In the following slides, consider an HRM consisting of $N+1$ PTP Instances and therefore N links (i.e., N hops)

Analysis of cTE Accumulation - 6

- Consider first cTE categories 1 and 2
- For these categories, cTE is fixed and permanent, for all time (i.e., for as long as the respective links and PTP Instances are in service.
  - This means that, if a particular path happens to have large cTE, the cTE will always be large for that path
  - In addition, category 2 cTE is due to components used in the respective PTP Instances. If the components in different PTP Instances are from the same vendor, the cTE in the different PTP Instances could be similar (or correlated). Also, there could be bias in the compensation procedures for link and node cTE.
  - It is true that category 1 and 2 cTE can be compensated. The cTE of interest here (i.e., the values of $D_{l,1}$ and $D_{n,2}$) of interest here are the values after any compensation
    - **In other words, the category 1 and 2 cTE of interest is the whatever cTE remains after compensation). This remaining cTE, while it might be small, will not be identically zero**

Analysis of cTE Accumulation - 7

- Given the above, the accumulation of category 1 and 2 cTE should be linear. The worst-case accumulated category 1 and 2 cTE is

$$\max\left|\text{cTE(accumulated, category 1 and 2)}\right| = ND_{n,2} + ND_{l,1}$$
$$= N(D_{n,2} + D_{l,1})$$

- In the above equation, it is assumed that the first and last PTP Instance contribute one-half the total $D_{n,2}$, as the first is the GM and has no ingress, and the last is the PTP End Instance or end application and has no egress

Analysis of cTE Accumulation - 8

- Next, consider cTE category 3
- For this category, cTE in each PTP Instance:
  - is independent of cTE in other PTP Instances
  - is different each time the PTP Instance is initialized
- With the above assumptions, the accumulated category 3 cTE is the sum of N random variables that are independent and identically distributed (and, actually, uniformly distributed)
- Then, by the Central Limit Theorem (which is a good approximation for $N = 64$ (and therefore also for $N = 100$)), the distribution of the accumulated cTE is approximately Gaussian (i.e., normal)

Analysis of cTE Accumulation - 9

- The accumulated category 3 cTE has zero mean and variance equal to

$$\sigma^2_{\text{accum, category 3}} = \frac{ND^2_{n,3}}{3}$$

- The maximum absolute value of accumulated category 3 cTE can be taken to be an upper quantile of the Gaussian distribution for the accumulated category 3 cTE that corresponds to a chosen number of standard deviations from the mean. Below are exceedance probabilities for several different numbers of standard deviations from the mean, for a Gaussian distribution

$$\Pr\{|x| > 6\sigma\} = \frac{2}{\sigma\sqrt{2\pi}} \int_{6\sigma}^{\infty} e^{-u^2/2\sigma^2} du = 1.9732 \times 10^{-9}$$

$$\Pr\{|x| > 5\sigma\} = 5.7330 \times 10^{-7}$$

$$\Pr\{|x| > 4\sigma\} = 6.3342 \times 10^{-5}$$

$$\Pr\{|x| > 7\sigma\} = 2.5596 \times 10^{-12}$$

Analysis of cTE Accumulation - 10

- In the quality control area, a 6-sigma criterion is often used, and that will be used here, i.e., we will take the maximum absolute value of accumulated cTE to be 6 standard deviations from the mean
- Then max|accumulated category 3 cTE| is equal to

$$\max|\mathrm{cTE}(\text{accumulated category 3})| = 6D_{n,3}\sqrt{\frac{N}{3}} = 3.464 D_{n,3}\sqrt{N}$$

- While the above accumulation of category 3 cTE goes asymptotically like the square root of N, note the presence of the multiplier 3.464
  - For $N \le 12$, $3.464 \ge N$, and the above result gives a larger answer than the result of simply multiplying $D_{n,3}$ by N.
    - For this case, linear accumulation is correct; the central limit theorem does not give a valid result for 6 standard deviations
  - For N moderately larger than 12, linear accumulation gives a reasonable conservative approximation.
  - For N much larger than 12 (e.g., 64), the above equation should be used

Analysis of cTE Accumulation - 11

- For $N = 100$, max|cTE| for the accumulated category 1 plus category 2 cTE is

$$\max|\mathrm{cTE}(\text{accumulated, category 1 and 2})| = 100(D_{n,2} + D_{l,1})$$

- In the above
  - $D_{n,2}$ = max|cTE| for a single PTP Instance for category 2, **after any compensation has been performed**
  - $D_{l,1}$ = max|cTE| for a single link (category 1), **after any compensation has been performed**
- **While it is expected that max|cTE| will be small after compensation, it will not be identically zero (i.e., a requirement must be specified)**

Analysis of cTE Accumulation - 12

- For $N = 100$, max|cTE| for the accumulated category 3 cTE is

$$\max|\text{cTE(accumulated category 3)}| = 6D_{n,3}\sqrt{\frac{100}{3}} = 34.64D_{n,3}$$

- In the above
  - $D_{n,3}$ = max|cTE| for a single PTP Instance for category 3
- **Note that while the above expression gives max|cTE| for the accumulated category 3 cTE that is less than linear (i.e., less than $100D_{n,3}$), it is larger than the square root of 100, i.e., 10, multiplied by $D_{n,3}$**

Analysis of cTE Accumulation - 13

- For $N = 64$, max|cTE| for the accumulated category 1 plus category 2 cTE is

$$\max|\mathrm{cTE}(\text{accumulated, category 1 and 2})| = 64(D_{n,2} + D_{l,1})$$

- In the above
  - $D_{n,2}$ = max|cTE| for a single PTP Instance for category 2, **after any compensation has been performed**
  - $D_{l,1}$ = max|cTE| for a single link (category 1), **after any compensation has been performed**
- **While it is expected that max|cTE| will be small after compensation, it will not be identically zero (i.e., a requirement must be specified)**

Analysis of cTE Accumulation - 14

- For $N = 64$, max|cTE| for the accumulated category 3 cTE is

$$\max\left|\text{cTE(accumulated category 3)}\right| = 6D_{n,3}\sqrt{\frac{64}{3}} = 27.71D_{n,3}$$

- In the above
  - $D_{n,3}$ = max|cTE| for a single PTP Instance for category 3
- **Note that while the above expression gives max|cTE| for the accumulated category 3 cTE that is less than linear (i.e., less than $64D_{n,3}$), it is larger than the square root of 64, i.e., 8, multiplied by $D_{n,3}$**

Review of max|dTE| Results from [3]

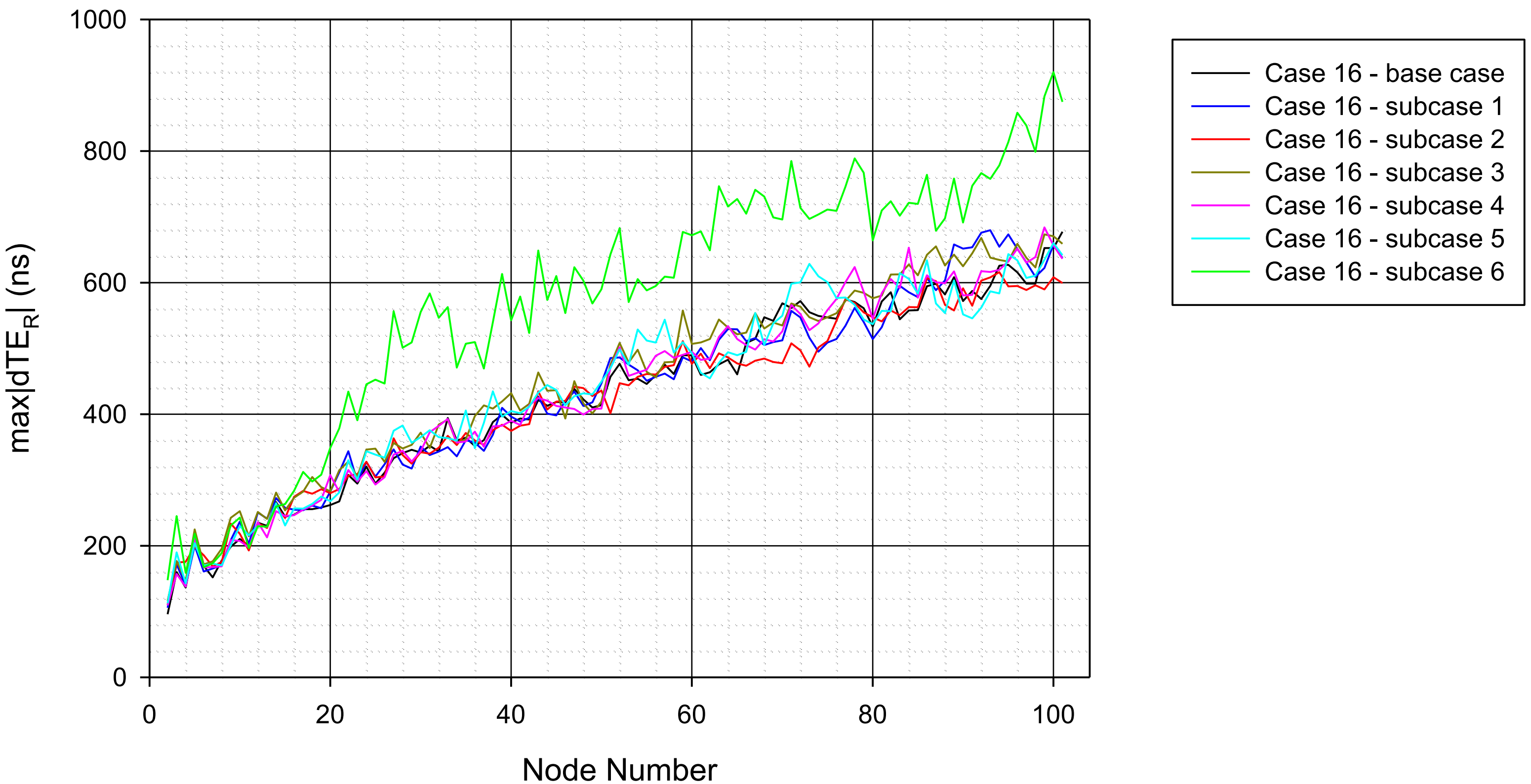
- The following six slides are taken from Reference [3] (which is Reference [1] of Reference [2]), and summarize the max|dTE_R| results obtained in the simulations presented there
- References in these six slides are references of [3]

Summary of Subcases of Case 16 Simulated

Subcase	Sync Interval variation (%)	Pdelay Interval variation (%)	Window Size for neighborRateRatio measurement
1	10	0	11
2	20	0	11
3	30	0	11
4	10	30	11
5	20	30	11
6	30	30	11
7	10	0	7
8	20	0	7
9	30	0	7
10	10	30	7
11	20	30	7
12	30	30	7

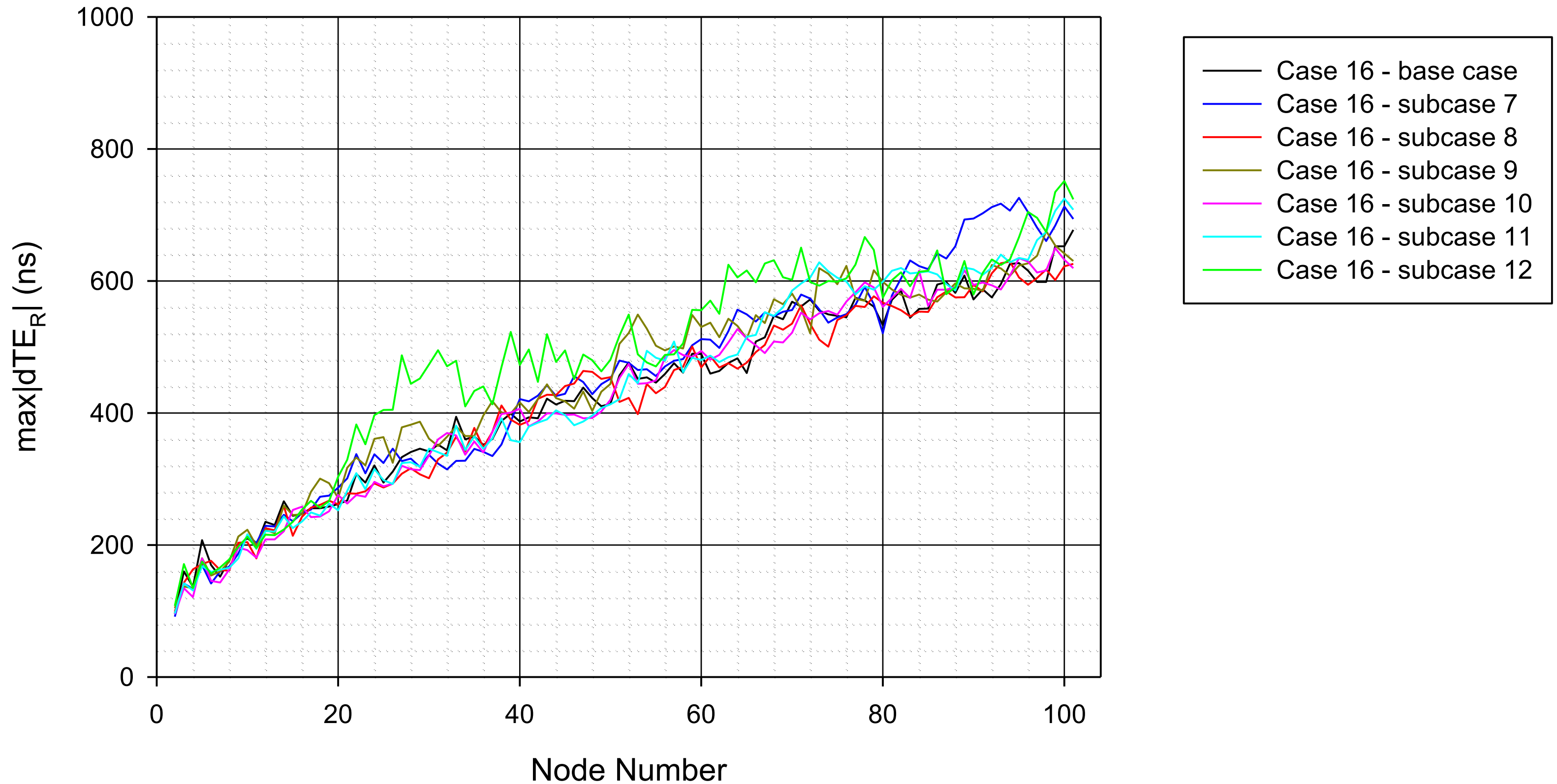
max|dTE$_R$| Results - 3

Case 16 - single replication results
Base case: no Sync or Pdelay interval variation
Subcases 1-3: Sync var (+/- 10, 20, 30%)
Subcases 4-6: Sync (+/- 10, 20, 30%) and Pdelay var (0-30%)
GM time error modeled
GM labeled node 1
Clock Model (all clocks): Frequency vs temperature stability and temperature vs time profile from [2]
Accumulate neighborRateRatio, which is measured with window of size 11 and median
KpKo = 11, KiKo = 65 (f3dB = 2.6 Hz, gain pk = 1.288 dB, zeta = 0.68219)



max|dTE$_R$| Results - 4

Case 16 - single replication results
Base case: no Sync or Pdelay interval variation
Subcases 7-9: Sync var (+/- 10, 20, 30%)
Subcases 10-12: Sync (+/- 10, 20, 30%) and Pdelay var (0-30%)
GM time error modeled
GM labeled node 1
Clock Model (all clocks): Frequency vs temperature stability and temperature vs time profile from [2]
Accumulate neighborRateRatio, which is measured with window of size 7 (11 for base case) and median
KpKo = 11, KiKo = 65 (f3dB = 2.6 Hz, gain pk = 1.288 dB, zeta = 0.68219)



max|dTE_R| Results - 3

Subcase	max|dTE_R|, 64 hops (ns)	max|dTE_R|, 100 hops (ns)
Base case	460	677
1	529	637
2	477	599
3	521	659
4	514	636
5	490	642
6	727	875
7	549	694
8	476	626
9	513	630
10	513	619
11	515	708
12	616	724

64 hops results are for node 65

100 hops results are for node 101

Base case is case 16 of [1], replication 1

Discussion of max|dTE_R| Results - 1

- The results for 64 hops range from 477 ns (subcase 2) to 727 ns (subcase 6), and all of them exceed the base case result of 460 ns
- The results for 100 hops range from 599 ns (subcase 2) to 875 ns (subcase6); 8 of the subcases have results that are less than the base case result of 677 ns
- Case 6, which has 30% variation for both Sync and Pdelay intervals and uses a window of size 11, is the worst case (this is clearly indicated in the plot showing subcases 1 – 6)
  - This is likely because the larger variation in the Pdelay interval and the larger window size results in a less accurate neighborRateRatio measurement, and larger Sync intervals for some Sync messages results in greater time error
- It is difficult to discern trends from the results due to their statistical variability
  - Other than the fact that case 6 has larger max|dTE_R| than the other cases, and that in general the variability of the Sync and Pdelay intervals results in larger max|dTE_R|, general trends are not evident
  - The plots of the multiple replication results in [1] (slides 14 and 15 of [1]) are much smoother)

Discussion of max|dTE_R| Results - 2

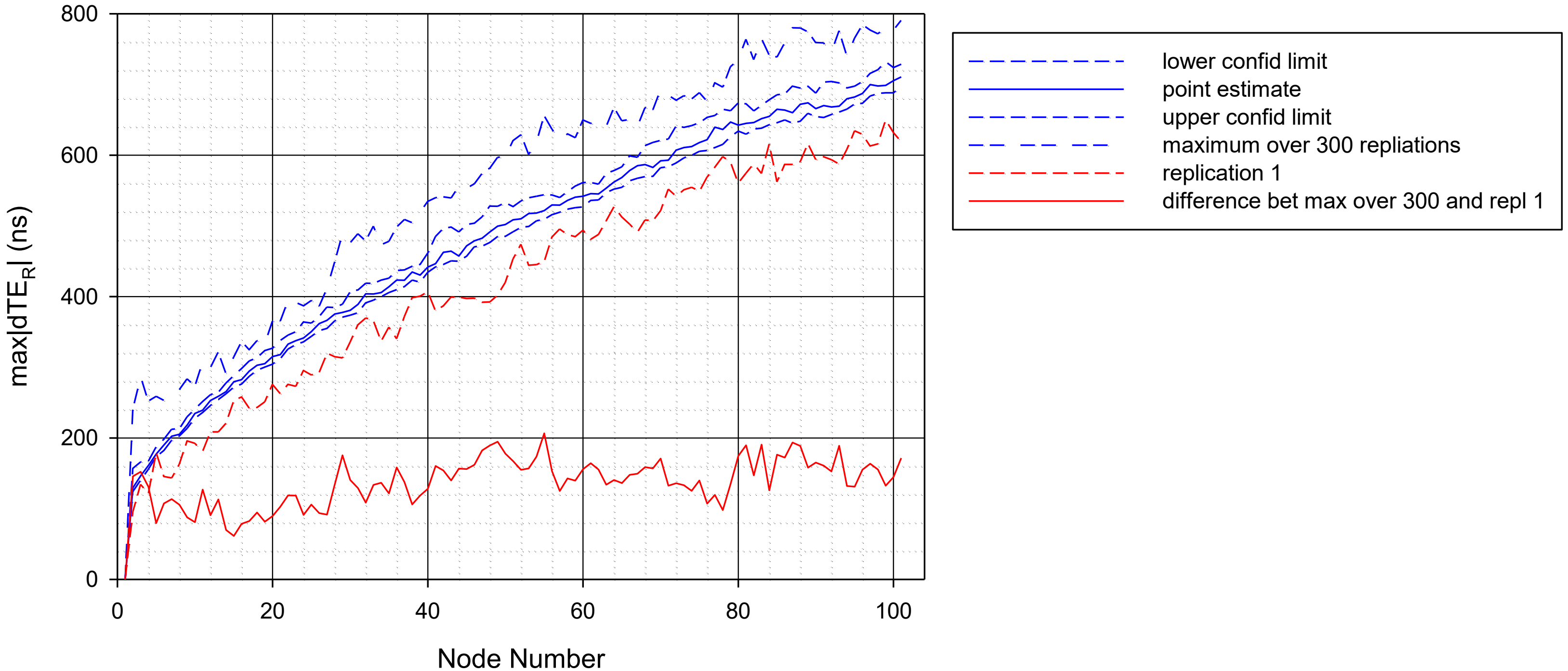
- In particular, it is not clear whether, in general, a window of size 7 gives better or worse results than a window of size 11
  - While the larger window averages (filters) more of the variability in the neighborRateRatio measurement, which improves the estimate, the actual frequency offset changes more during the duration of the larger window, which makes the estimate worse
- It appears possible to meet the 1 μs objective over 64 hops, and over 100 hops if possible, but subject to the margin needed for cTE
  - Note that the results will increase when multiple replications of the simulations are run; the increase could be as much as 100 – 250 ns
    - This was observed previously for case 16, where the multiple replication results were 710 ns and 815 ns for nodes 64 and 100, respectively (see slide 20 of [1]), and the single replication results were 460 ns and 677 ns, respectively (see the base case in slide 31 above, which is for replication 1 but with GM time error modeled)

New Multiple Replication dTE simulations

- After discussion of [1], it was decided to run 300 multiple, independent replications of a simulation for subcase 10 above (of case 16)
- The next slide summarizes the 300 multiple replication results for subcase 10, and also shows the single replication results from [3] (these are also for replication 1) and the difference between the single and multiple replication results
- The new results indicate that:
  - The maximum dynamic relative time error is approximately 800 ns
  - The largest increase in max|dTE_R| for the multiple replication results, compared to thesingle replication results, is approximately 200 ns
- The slide after the next slide shows the fractional increase of max|dTE_R| for 300 multiple replications compared to replication 1 (single replication)
  - After 64 hops, the fraction is in the 1.2 to 1.3 range

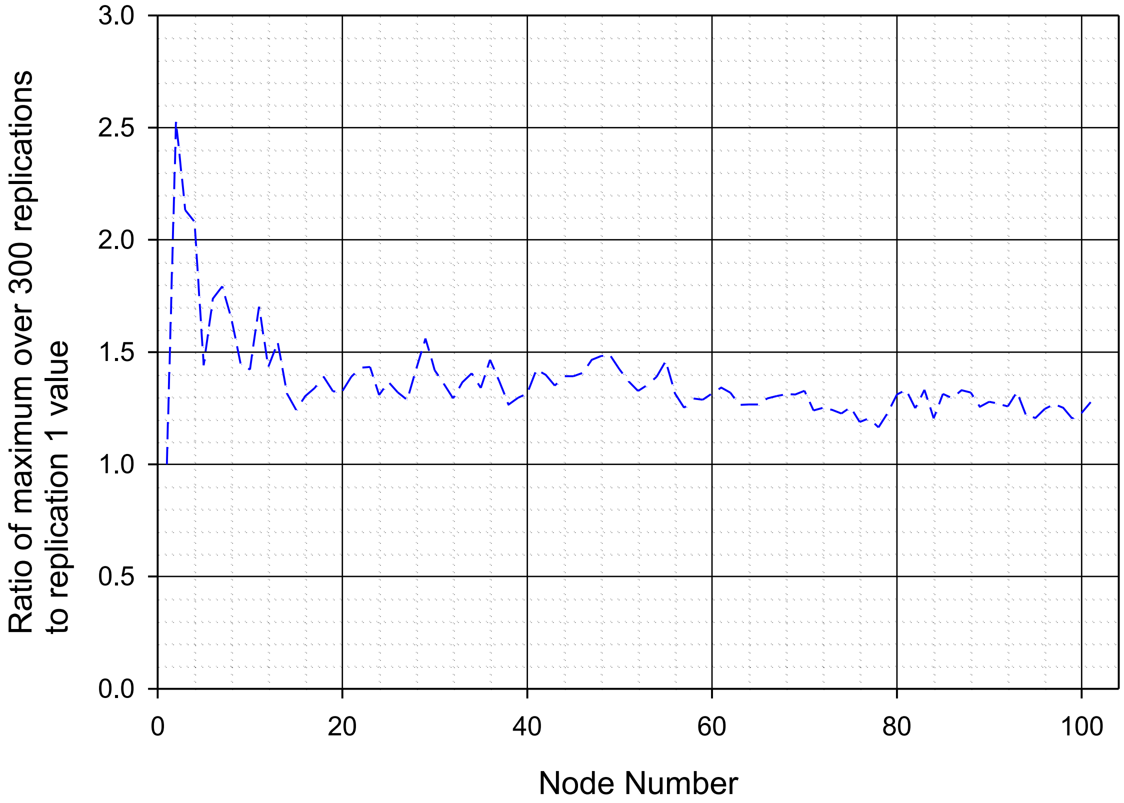
Multiple Replication Results for Subcase 10 - 1

Cases 16, Subcase 10 - multiple replication results
GM time error modeled
GM labeled node 1
Clock Model (all clocks): Frequency vs temperature stability and temperature vs time profile from [2]
Accumulate neighborRateRatio, which is measured with window of size 11 and median
KpKo = 11, KiKo = 65 (f3dB = 2.6 Hz, gain pk = 1.288 dB, zeta = 0.68219)



Multiple Replication Results for Subcase 10 - 2

Cases 16, Subcase 10 - multiple replication results
GM time error modeled
GM labeled node 1
Clock Model (all clocks): Frequency vs temperature stability and temperature vs time profile from [2]
Accumulate neighborRateRatio, which is measured with window of size 11 and median
KpKo = 11, KiKo = 65 (f3dB = 2.6 Hz, gain pk = 1.288 dB, zeta = 0.68219)



Budgeting and cTE Equipment Requirements

- The following slides are taken from [1] and modified to account for the new multiple replication results for subcase 10

Budgeting and cTE Equipment Requirements - 64 Hops - 1

- From slide 23, max|dTE| for 64 hops, for the 12 single-replication cases simulated in [3], ranges from 477 – 727 ns for subcases 1 – 6 (window size of 11 for neighborRateRatio measurement) and 476 – 616 ns for subcases 7 – 12 (window size of 7 for neighborRateRatio measurement)
  - 477 ns: subcase 2
  - 727 ns: subcase 6
  - 476 ns: subcase 8
  - 616 ns: subcase 12
- The results indicate that subcases 7 – 12 (window size 7) give better results; these results will be used for the budgeting

Budgeting and cTE Equipment Requirements - 64 Hops - 2

- The new, multiple replication results for subcase 10 indicate that results for multiple replications can exceed results for single replications by as much as 200 ns
- Taking 816 ns as the multiple replication estimate of max|dTE$_R$| for 64 hopes leaves 184 ns for cTE
- For 64 hops, the tentative estimate of the budget for cTE is 184 ns
- Using the results on slides 17 and 18, and noting that the cTE results for categories 1 and 2 and the results for category 3 can be added, produces

$$
\begin{aligned}
\max|\mathrm{cTE}| &= 64(D_{n,2} + D_{l,1}) + 27.71 D_{n,3} \\
&= 64(D_{n,2} + D_{l,1} + 0.4330 D_{n,3})
\end{aligned}
$$

Budgeting and cTE Equipment Requirements - 64 Hops - 3

- The above produces

$$D_{n,2} + D_{l,1} + 0.4330 D_{n,3} \le \frac{184 \text{ ns}}{64}$$

- Or (and after rounding to 2 significant digits)

$$D_{n,2} + D_{l,1} + 0.4330 D_{n,3} \le 2.875 \text{ ns} \approx 2.9 \text{ ns}$$

- The actual limit for a single PTP Instance plus link depends on the fraction of cTE that is category 1 and 2 versus category 3
  - If all the cTE is category 1 and 2, the limit is 2.9 ns
  - If all the cTE is category 3, the limit is 2.9 ns/0.4330 = 6.70 ns
  - In reality, the limit is probably somewhere in between the two values

Budgeting and cTE Equipment Requirements - 100 Hops - 1

- From slide 23, max|dTE| for 100 hops, for the 12 single-replication cases simulated in [3], ranges from 599 – 875 ns for subcases 1 – 6 (window size of 11 for neighborRateRatio measurement) and 626 – 724 ns for subcases 7 – 12 (window size of 7 for neighborRateRatio measurement)
  - 599 ns: subcase 2
  - 875 ns: subcase 6
  - 626 ns: subcase 8
  - 724 ns: subcase 12
- As for 64 hops, the results for 100 hops indicate that subcases 7 – 12 (window size 7) give better results; these results will be used for the budgeting
  - The subcases corresponding to the upper and lower ends of each range are the same as for 64 hops

Budgeting and cTE Equipment Requirements - 100 Hops - 2

- The new, multiple replication results for subcase 10 indicate that results for multiple replications can exceed results for single replications by as much as 200 ns
- Taking 924 ns as the multiple replication estimate of max|dTE_R| for 64 hopes leaves 76 ns for cTE
- For 100 hops, the tentative estimate of the budget for cTE is 76 ns
- Using the results on slides 17 and 18, and noting that the cTE results for categories 1 and 2 and the results for category 3 can be added, produces

$$\begin{aligned}\max|\mathrm{cTE}| &= 100(D_{n,2} + D_{l,1}) + 34.64D_{n,3} \\ &= 100(D_{n,2} + D_{l,1} + 0.3464D_{n,3})\end{aligned}$$

Budgeting and cTE Equipment Requirements - 100 Hops - 3

- The above produces

$$D_{n,2} + D_{l,1} + 0.3464 D_{n,3} \le \frac{76 \text{ ns}}{100}$$

- Or (and after rounding to 2 significant digits)

$$D_{n,2} + D_{l,1} + 0.3464 D_{n,3} \le 0.76 \text{ ns}$$

- The actual limit for a single PTP Instance plus link depends on the fraction of cTE that is category 1 and 2 versus category 3
  - If all the cTE is category 1 and 2, the limit is 0.76 ns
  - If all the cTE is category 3, the limit is 0.76 ns/0.3464 = 2.2 ns
  - In reality, the limit is probably somewhere in between the two values

Budgeting and cTE Equipment Requirements - 100 Hops - 4

- The range 0.76 – 2.2 ns for the cTE limit, for a single piece of equipment and single link, for 100 hops is very tight
  - The estimated range of [1], which was based on a larger max|dTE_R| increase for multiple replications relative to single replications (250 ns, versus 200 ns obtained in the new simulations) was 0.26 – 0.75 ns, i.e., it was even tighter. However, the new range of 0.76 – 2.2 ns is still very tight.
- Examining the max|dTE| results for subcases 7 – 12 for 100 hops indicates that cases 8 – 10 are best (619 – 630 ns), but cases 7, 11, and 12 are close to or exceed 700 ns
  - If the simulated max|dTE| could be kept to 600 – 650 ns, then the estimate of max|dTE| for multiple replications would be 800 – 850 ns
  - This would leave 150 – 200 ns for cTE
  - Using 150 ns, the range for the cTE requirement, would be 1.5 – 4.3 ns

Budgeting and cTE Equipment Requirements Based on Subcase 10 - 1

- The above results are based on the worst-case of subcases 7 – 12
- Results can also be obtained for subcase 10
  - This corresponds to using the subcase 10 assumptions (i.e., ±10% Sync interval variation, 30% Pdelay interval variation, window of size 7) as the basis for requirements
- From the results plot on slide 27, for subcase 10:
  - $\max|dTE_R|$ = 800 ns (100 hops)
  - $\max|dTE_R|$ = 670 ns (64 hops)
- Then, assuming subcase 10, the total cTE budget is:
  - 200 ns (100 hop HRM)
  - 330 ns (64 hop HRM)

Budgeting and cTE Equipment Requirements Based on Subcase 10 - 2

- For a 100-hop HRM, this produces:

$$D_{n,2} + D_{l,1} + 0.3464 D_{n,3} \le \frac{200 \text{ ns}}{100} = 2 \text{ ns}$$

  - If all the cTE is category 1 and 2, the limit is 2 ns
  - If all the cTE is category 3, the limit is 2 ns/0.3464 = 5.8 ns
  - In reality, the limit is probably somewhere in between the two values

- For a 64-hop HRM, this produces:

$$D_{n,2} + D_{l,1} + 0.3464 D_{n,3} \le \frac{330 \text{ ns}}{64} = 5.16 \text{ ns} \cong 5.2 \text{ ns}$$

  - If all the cTE is category 1 and 2, the limit is 5.2 ns
  - If all the cTE is category 3, the limit is 5.2 ns/0.4430 = 11.6 ns
  - In reality, the limit is probably somewhere in between the two values

Conclusion - 1

- The budget for cTE, out of the total 1 μs objective, is (**assuming a 200 ns increase in max|dTE$_R$| for multiple versus single-replication results for subcase 10**):
  - 184 ns (64-hop HRM, based on subcases 7 – 12)
  - 76 ns (100-hop HRM, based on subcases 7 - 12)
  - 105 ns (100-hop HRM, based on subcases 8 – 10)
- The resulting cTE requirement is in the range:
  - 2.9 ns – 6.7 ns (64-hop HRM, based on subcases 7 - 12)
  - 0.76 ns – 2.2 ns (100-hop HRM, based on subcases 7 - 12)
  - 1.5 ns – 4.3 ns (100-hop HRM, based on subcases 8 – 10)
- The reason the cTE requirement is stated as a range is that the requirement depends on what fraction of cTE is category 1 and 2, versus category 3
- Since it is not known, a priori, what this fraction is, the lower end of the range should be used
- **In all cases, the cTE requirement is extremely stringent**
  - **It appears that, to meet the 1 μs requirement, cTE must be kept to the order of 3 – 6 ns/hop for a 64-hop HRM and 1 – 2 ns/hop for a 100-node HRM**
  - **Note that these cTE limits are on remaining cTE after any compensation**

Conclusion - 2

- If subcase 10 is assumed, the budget for cTE, out of the total 1 μs objective, is:
  - 330 ns (64-hop HRM)
  - 200 ns (100-hop HRM)
- The resulting cTE requirement is in the range:
  - 5.2 ns – 11.6 ns (64-hop HRM)
  - 2.9 ns – 6.7 ns (100-hop HRM)
- As above, the reason the cTE requirement is stated as a range is that the requirement depends on what fraction of cTE is category 1 and 2, versus category 3
- Since it is not known, a priori, what this fraction is, the lower end of the range should be used
- **Compared to the results for the worst-case of subcases 7 – 12, the cTE requirement is still very stringent**
  - **It appears that, to meet the 1 μs requirement, cTE must be kept to the order of 5 – 12 ns/hop for a 64-hop HRM and 3 – 7 ns/hop for a 100-node HRM**
  - **Note that these cTE limits are on remaining cTE after any compensation**

Next Steps

- It should be decided what practical limit on cTE is achievable, for each category
  - cTE due to physical link asymmetry
  - cTE due to asymmetry within the PTP Instance (i.e., node) that is fixed and constant for all time
  - cTE associated with the PTP Instance (i.e., node) that is fixed while the node is up and operating, but changes when the node (or port if this cTE is associated only with the port) re-initializes
- **Note that these cTE limits are on remaining cTE after any compensation**
- Also, any changes to existing assumptions that would decrease dTE would result in more budget for cTE, for example:
  - Smaller residence time
  - more constrained temperature profile
  - More stable oscillator (with respect to temperature variation)
- Finally, it was stated that the desire is to meet the 1 μs objective for the 100 hop HRM case **if possible**
  - It might be decided that meeting the objective for 100 hops is not practical

Thank you

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[1] Geoffrey M. Garner, *Analysis of Constant Time Error Accumulation and Budgeting in an IEC/IEEE 60802 Network*, IEC/IEEE 60802 presentation, July 12, 2021 (available at https://www.ieee802.org/1/files/public/docs2021/60802-garner-analysis-of-cTE-and-budgeting-in-60802-network-0721-v00.pdf)

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[4] Geoffrey M. Garner, *New Simulation Results for dTE for an IEC/IEEE 60802 , Based on New Frequency Stability Model, Revision 1*, IEC/IEEE 60802 presentation, June 16, 2021 (available at https://www.ieee802.org/1/files/public/docs2021/60802-garner-multipe-replic-simulation-results-new-freq-stab-model-0421-v02.pdf)

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[6] Geoffrey M. Garner, *Summary of Assumptions for Next Simulations, based on Presentation and Subsequent Discussion of [1], Revision 1*, IEC/IEEE 60802 presentation, March 11, 2021 (available at https://www.ieee802.org/1/files/public/docs2021/60802-garner-summary-of-assumptions-next-simulations-0321-v01.pdf)