Simulation of a Chain of Clocks

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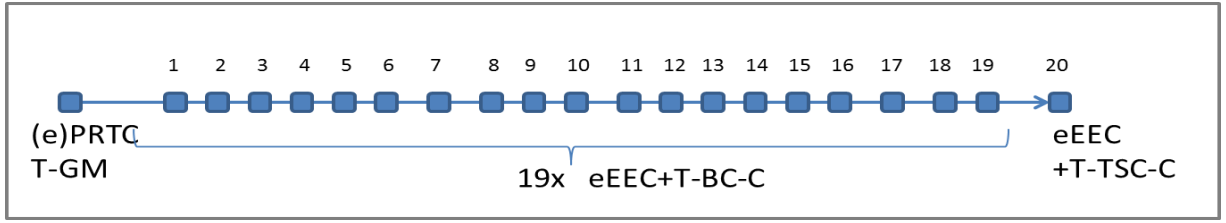
Outline of Presentation

- Some Background
- Chain of clocks (eHRMa and eHRMc)
  - Start of chain : ePRTC (variants: PRTC-A and PRTC-B)
  - End of chain : T-TSC (with eEEC; variant with EEC)
  - Intermediate clocks : T-BC (with eEEC; variant with EEC)
- Mathematical Model for analysis
- Comparison of Time-domain and Frequency-domain methods
- Frequency models for EEC, eEEC, ePRTC (and PRTC-A, PRTC-B)
- Some results (the full set in back-up)
- Summary

Some Background

- Motivations for this study
  - Establish a suitable wander generation TDEV mask for the enhanced Ethernet Equipment Clock (eEEC) addressed in G.8262.1
  - Analyze impact of bandwidth of phy_layer in conjunction with packet_layer
  - Provide a rapid (not time-consuming) approach to estimate timing behavior
- The underlying premise: Analytical approach
  - Frequency domain approach using power-spectral density functions and numerical integration to estimate standard deviation (e.g. TDEV)
  - Other Metrics (MTIE, max|TE|) involving “peak” and “maximum” estimated as G times standard deviation (G is about 4.0 to 8.0)
  - All noise sources are uncorrelated so that they add in power (variance)
  - **Frequency offsets, constant Time Error (cTE), asymmetry effects, deterministic signals, and time-varying phenomena are not included**

Chain of clocks (eHRMa and eHRMc)

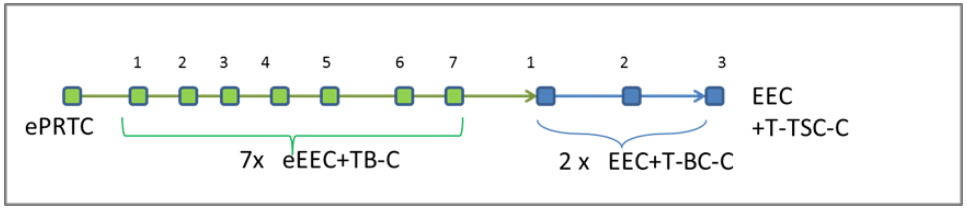


eHRMa

C412_Fig. 2.1.1. eHRMa (see WDeTSSLD-Rev11.docx)

Chain eHRMa1 is essentially eHRMa with the ePRTC replaced by a PRTC-A

Chain eHRMa2 is essentially eHRMa with the ePRTC replaced by a PRTC-B



eHRMc

C415_Fig. 2.1.1. eHRMc (see WDeTSSLD-Rev11.docx)

Chain eHRMc1 is essentially eHRMc with the ePRTC replaced by a PRTC-A

Chain eHRMc2 is essentially eHRMc with the ePRTC replaced by a PRTC-B

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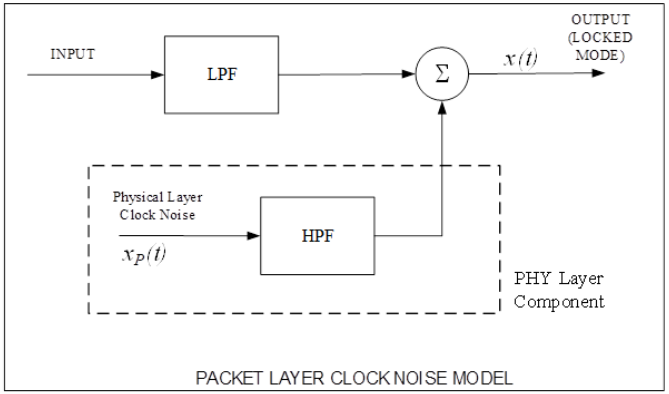
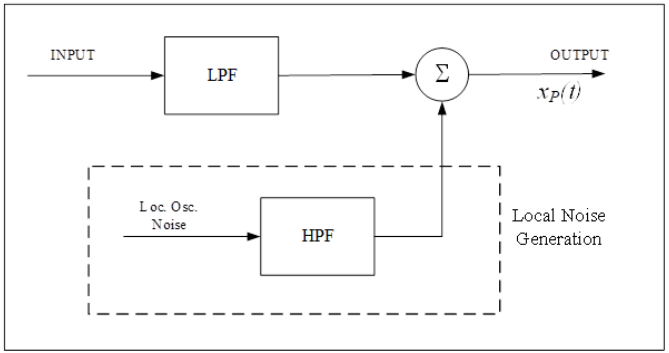
Mathematical model for analysis



- Time layer clock noise model
- "Input" of clock *n* is output of clock (*n*-1) plus time-stamping noise of clock *n*
- Physical layer clock modeled as wander generation limit
- NOTE: Time holdover of (time-)clock *n* is equivalent (clock noise) to output of physical layer clock *n*



- Physical layer clock noise model
- Input of clock n is output of clock (*n*-1)
- Local noise generation equivalent to wander generation in locked mode
- Output of clock *n* also goes to time-layer of clock *n*

Analysis is done in frequency domain

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Mathematical formulation

Assumed packet rate = 16 packets/sec --- sampling rate f_0 = 16Hz;
sampling interval τ_0 = 0.0625s

$$\sigma_x^2(\tau = n \cdot \tau_0) = G(n) \cdot \int_0^{0.5 \cdot f_0} S_x(f) \cdot \frac{(\sin(n \pi f \tau_0))^6}{(\sin(\pi f \tau_0))^2} df$$

TVAR from spectrum

$$\sigma_\xi^2(n) \approx \int_0^{f_0} S_x(f) \cdot 4 \cdot (\sin(n \pi f \tau_0)^2) df$$

$$M_x(\tau) \leq 7 \cdot \sigma_\xi(n)$$

MTIE from spectrum
{ maximum = 7 · sigma }

$$maxTE = 4.0 \cdot \sigma_x(0)$$

$$\sigma_x^2 = \int S_x(f) df$$

Max|TE| from spectrum
{ maximum = 4·sigma & 8·sigma considered}

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Comparison of simulation methods

- There are two distinct approaches (frequency domain and time domain):
  - Model signals in the frequency domain in terms of power spectrum
    - The discrete-time signals must have a power spectrum equivalent to the desired (noise)
    - Implement “filters” as multiplication of power-spectrum function by squared magnitude frequency response function or as difference equations operating on the discrete-time signals
  - Model signals in time domain as discrete-time signals (sequences {x(n)})
    - The difference equations must have an underlying frequency response equivalent to the desired filter characteristic
    - Time-domain approach can accommodate deterministic (e.g. sinusoidal) signals
- Acknowledge collaborative work by Geoff Garner:
  - Test cases showed matching results for the two approaches

Comparison of the methods (Pros and Cons)

- The time-domain approach:
  - Can simulate the system behavior more closely by including time-varying aspects and sinusoidal components, delays, and non-linear effects
  - Noise strength (maximum values) obtained directly by observation
  - Noise strength significance is affected by duration of simulation (number of samples of output computed) and can therefore require significant computation time
  - Using pre-computed noise sequences can reduce effort but requires verification of uncorrelated behavior

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Comparison of the methods (Pros and Cons)

- The frequency-domain approach:
  - Require less computation time
  - Independence of different noise sources is “automatic” (addition in power)
  - Can handle only those signals that have a power-law spectrum (no deterministic components like sinusoids)
  - Noise strength estimated in terms of standard deviation requiring some assumptions to translate to “maximum”
  - Deriving MTIE and Max|TE| from spectrum yields very conservative (pessimistic) values when the integration interval is long

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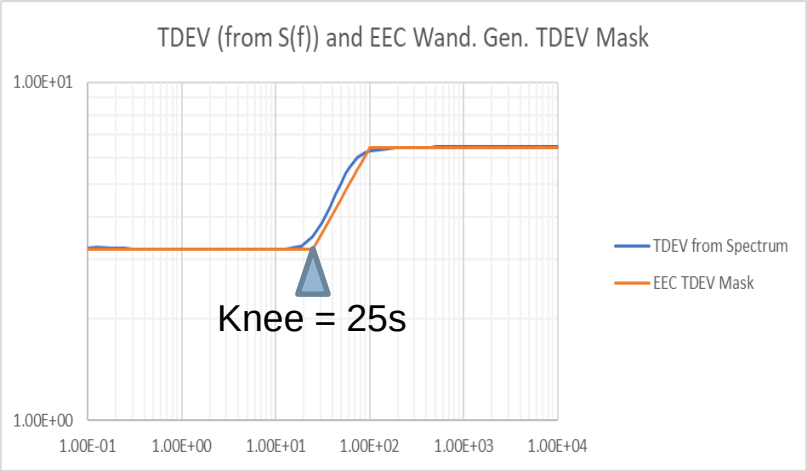
EEC/eEEC Wander Generation TDEV Mask

$$S_x(f) = \left(\frac{G}{f} \cdot (a_1 \cdot H_1(f) + a_2 \cdot H_2(f))\right) \cdot C(f)$$

$H_1(f)$: 2nd order high-pass filter; $H_2(f)$: 3rd order low-pass filter; $(1/f)$: spectral density shape of flicker phase noise

For eEEC: power-spectral-density = *scale-factor**(EEC_PSD)



scale-factor = α

Three choices of α considered (0.5, 0.3535, 0.19)

$$S_x(f) = \alpha \cdot \left(\frac{G}{f} \cdot (a_1 \cdot H_1(f) + a_2 \cdot H_2(f))\right) \cdot C(f)$$

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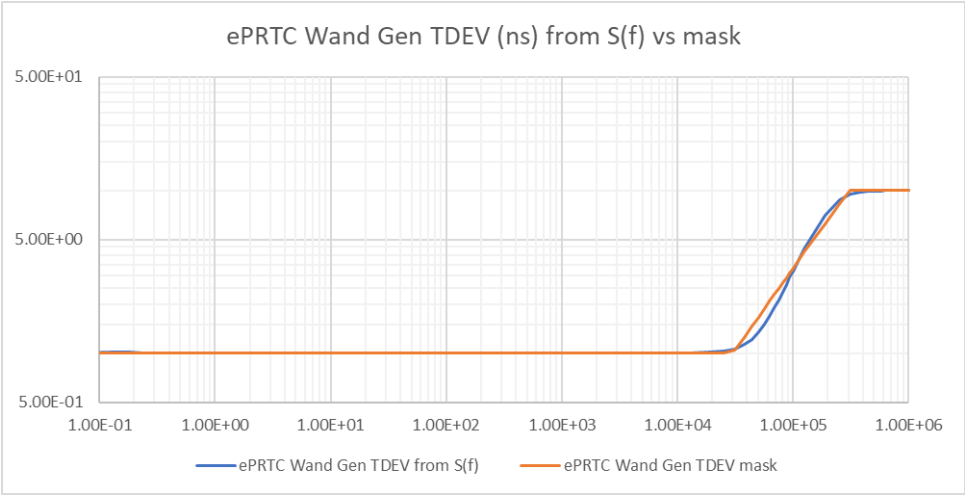
ePRTC Wander Generation TDEV Mask

$$S_x(f) = \left(\frac{G}{f}\right) \cdot (1 + 100.0 \cdot H_L(f)) \cdot C(f)$$

- G ~0.44.
- $H_L(f)$ is a fourth-order low-pass filter characteristic with 3dB cut-off frequency = 0.000002 Hz.
- *(1/f) :* spectral density shape of flicker phase noise



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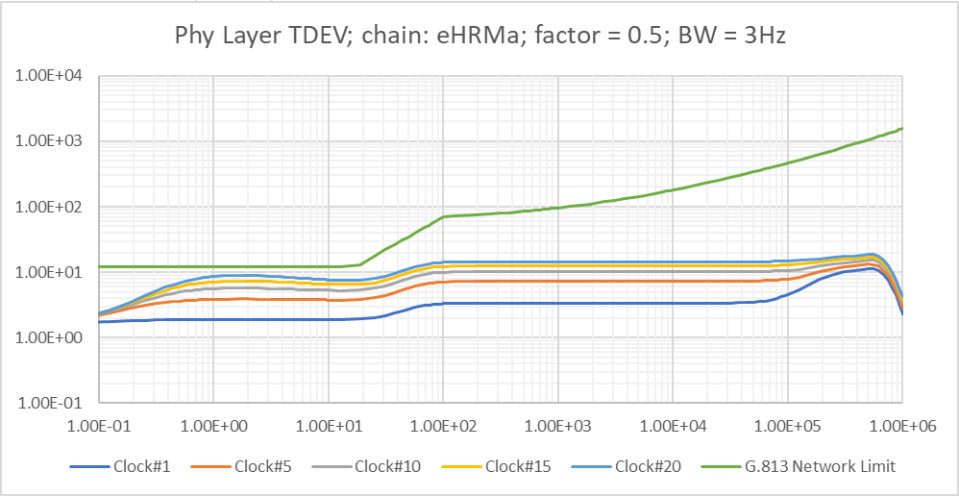
Physical Layer Clock(s): eHRMa

Phy Layer TDEV (Clock#20 is at end of chain)



- One case shown: scale-factor = 0.5; BW = 3Hz; results for cases where scale-factor = 0.3535 and 0.19 are available.
- Good match with time-domain method.
- G.8261/G.813 network limit can be met with scale-factor = 0.5; smaller scale-factors provide more margin.

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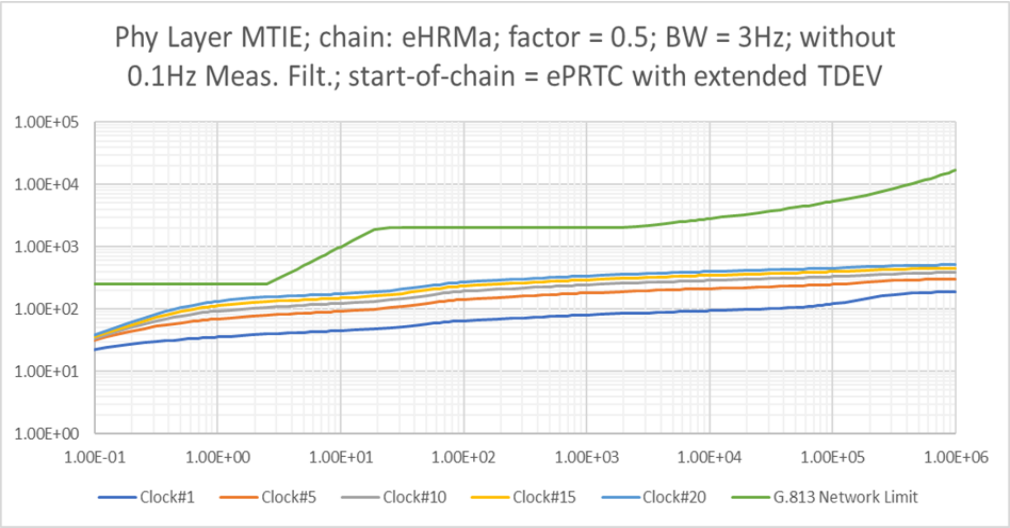
Physical Layer Clock(s): eHRMa

Phy Layer MTIE (Clock#20 is at end of chain)



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- Good match with time-domain method.
- G.8261/G.813 network limit can be met with scale-factor = 0.5; smaller scale-factors provide more margin.

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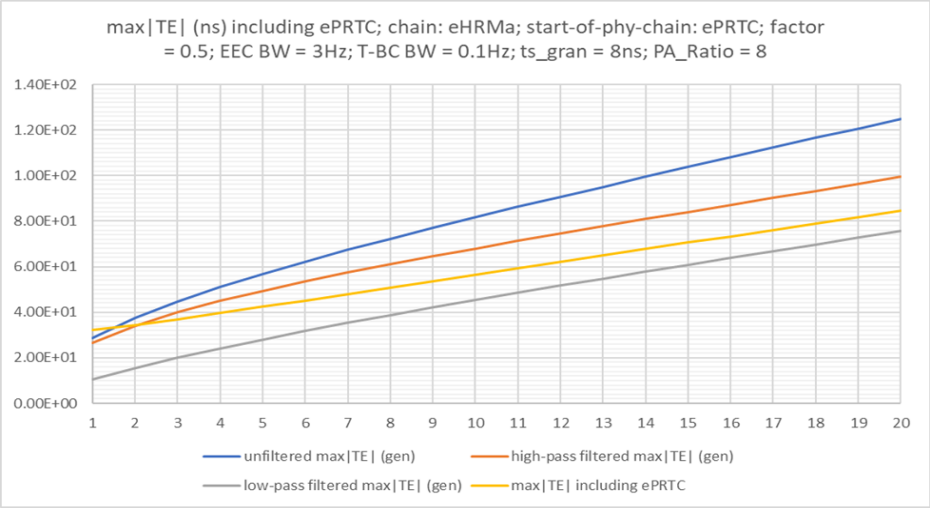
Packet Layer Clock(s): eHRMa

Packet Layer Max|TE| (Clock#20 is at end of chain)



- One case shown: scale-factor = 0.5; BW = 3Hz; results for cases where scale-factor = 0.3535 and 0.19 are available.
- Compared with time-domain method the frequency domain approach is conservative (uses a peak-to-rms ratio of 8).
- Max|TE| at clock output obtained by starting chain time-layer with noise-free ePRTC and adding in the effect of the ePRTC at each clock to the filtered time error. The addition is done incoherently.

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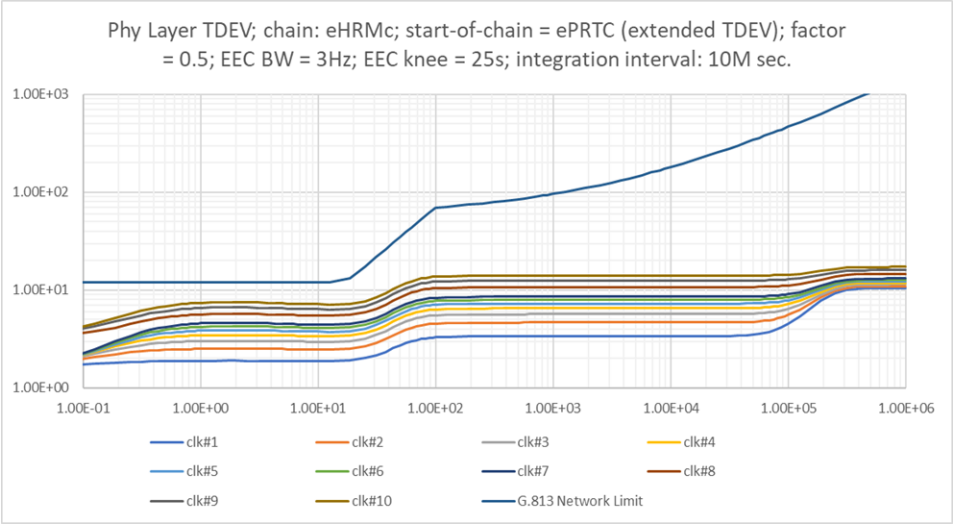
Physical Layer Clock(s): eHRMc (start-of-chain ePRTC)

Phy Layer TDEV (Clock#10 is at end of chain)



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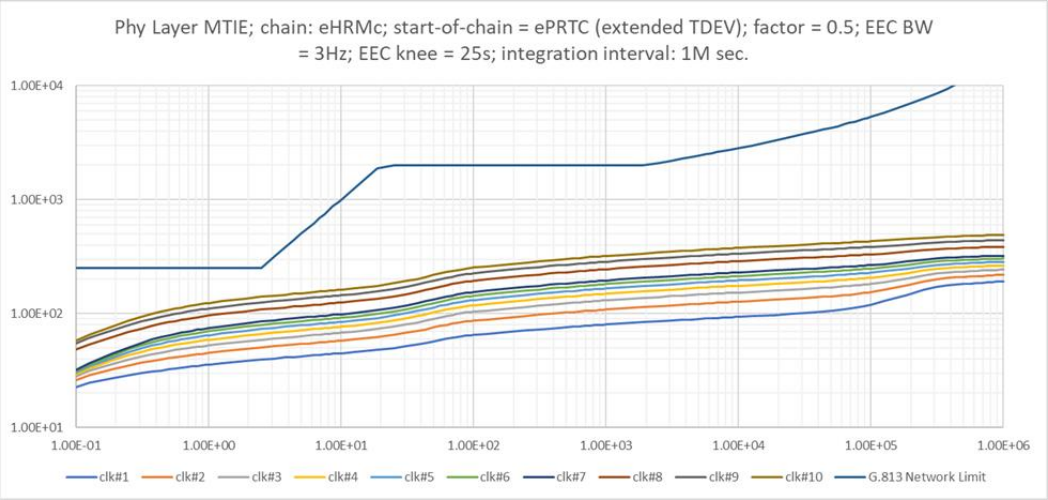
Physical Layer Clock(s): eHRMc (start-of-chain = ePRTC)

Phy Layer MTIE (Clock#10 is at end of chain)



- One case shown: scale-factor = 0.5; BW = 3Hz; results available for cases where scale-factor = 0.3535 and 0.19.
- Compared with time-domain method the frequency domain approach is conservative (factor of ~1.3).
- G.8261/G.813 network limit can be met with scale-factor = 0.5; smaller scale-factors provide more margin.

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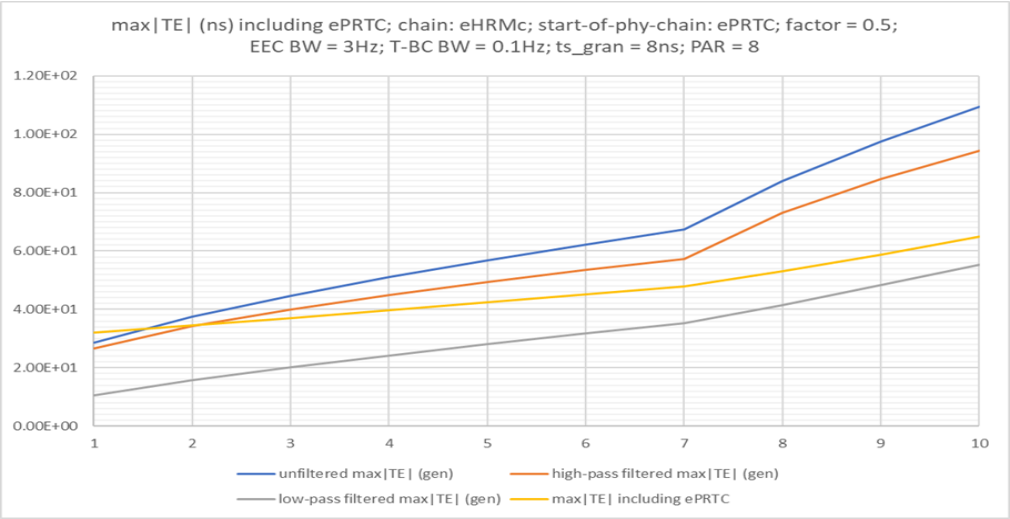
Packet Layer Clock(s): eHRMc (start-of-chain = ePRTC)

Packet Layer Max|TE| (Clock#10 is at end of chain)



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- Compared with time-domain method the frequency domain approach is conservative (uses a peak-to-rms ratio of 8).
- Max|TE| at clock output obtained by starting chain time-layer with noise-free PRTC and adding in the effect of the ePRTC at each clock to the filtered time error. The addition is done incoherently.

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Summary of simulation results: Chain of Clocks

- For achieving the G.8261/G.813 network limit, the eEEC wander generation TDEV can be 0.5times (or smaller) than the EEC requirement. This is for both TDEV and MTIE and for 20 clocks (eHRMa) and 10 clocks (eHRMc) and also for PTRC choices of ePRTC, PRTC-A and PRTC-B
- For Max|TE|, assuming a peak-to-rms ratio of 8 (& T-BC BW=0.1Hz; EEC-BW = 3Hz; 8ns time-stamping granularity) the contribution of the physical_layer impact on time layer (at last clock) is:

Scale-Factor	20 clocks (eHRMa and derivatives)			10 clocks (eHRMc and derivatives)		
	ePRTC	PRTC-A	PRTC-B	ePRTC	PRTC-A	PRTC-B
0.5	75.7ns	83.7ns	75.7ns	55.4ns	62.6ns	55.4ns
0.3535	54.4ns	32.5ns	54.4ns	47.7ns	55.9ns	47.7ns
0.19	31.5ns	47.6ns	31.5ns	41.3ns	50.6ns	41.3ns

The PRTC contribution (30ns, 100ns, 40ns for ePRTC, PRTC-A, and PRTC-B) is added incoherently to get the total Max|TE|.
Note: Constant Time Error (cTE) and effects of asymmetry have not been included.

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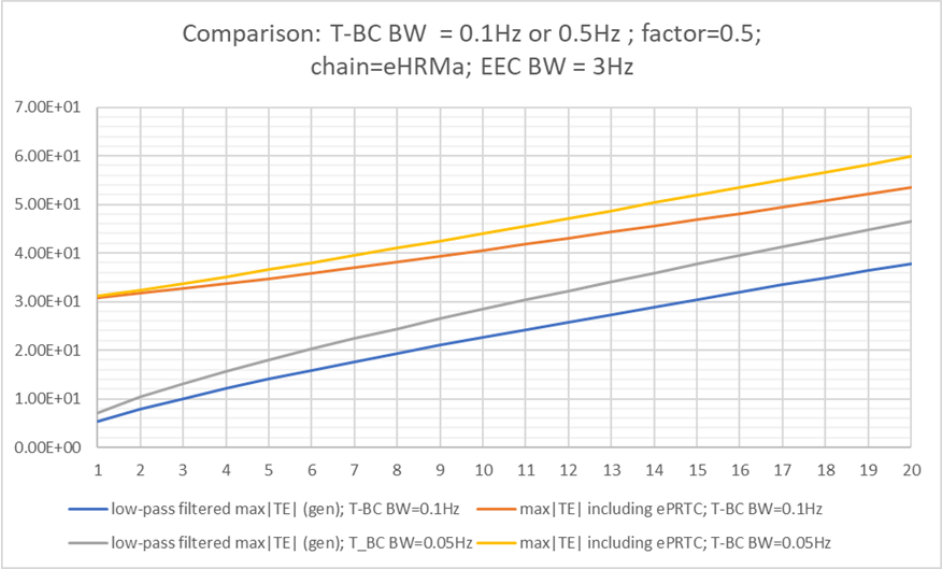
Impact of T-BC Bandwidth

- T-BC bandwidth must be between 0.05Hz and 0.1Hz (G.8273.2)
- Observation: There not a significant difference between 0.05Hz and 0.1Hz for T-BC bandwidth with 0.1Hz being marginally better (caveat: not all cases were tried).



Results available for cases with scale-factor values of 0.3535 and 0.19.

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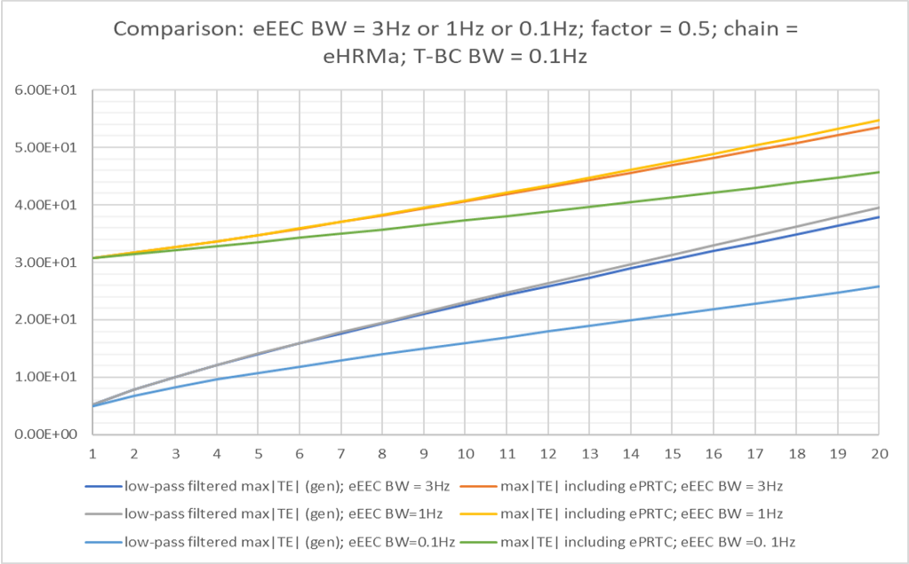
Impact of eEEC Bandwidth on Packet Layer Clock

- Simulations to investigate the impact of eEEC bandwidth on Max|TE|; proposed bandwidth specification is between 1Hz and 3Hz.
- Observation: There was not a significant difference between 1Hz and 3Hz for eEEC bandwidth. There was a noticeable improvement for eEEC bandwidth of 0.1Hz (caveat: T-BC BW of 0.1Hz was used).



Results available for cases with scale-factor values of 0.3535 and 0.19.

Concluding Remarks

- The results obtained by the frequency-domain and time- domain methods show good agreement.
- The frequency-domain method is computationally rapid and can provide results quickly, allowing analysis of several “what if?” scenarios in a timely fashion.
- In order to meet the physical layer network limits, it suffices that the eEEC be twice as good (scale-factor of 0.5) as the regular EEC.
- The best performance is obtained when phy_layer (eEEC) and packet_layer(T-BC) bandwidths are the same (especially important for last clock in chain)
- Care must be taken to incorporate the time error of the PRTC. The approach taken here is to start the chain with “zero” and add (in power) the worst case PRTC time error at the clock output being measured.
- Back-up slides address the cases where the start-of-chain is a PRTC-A or PRTC-B.

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Questions?

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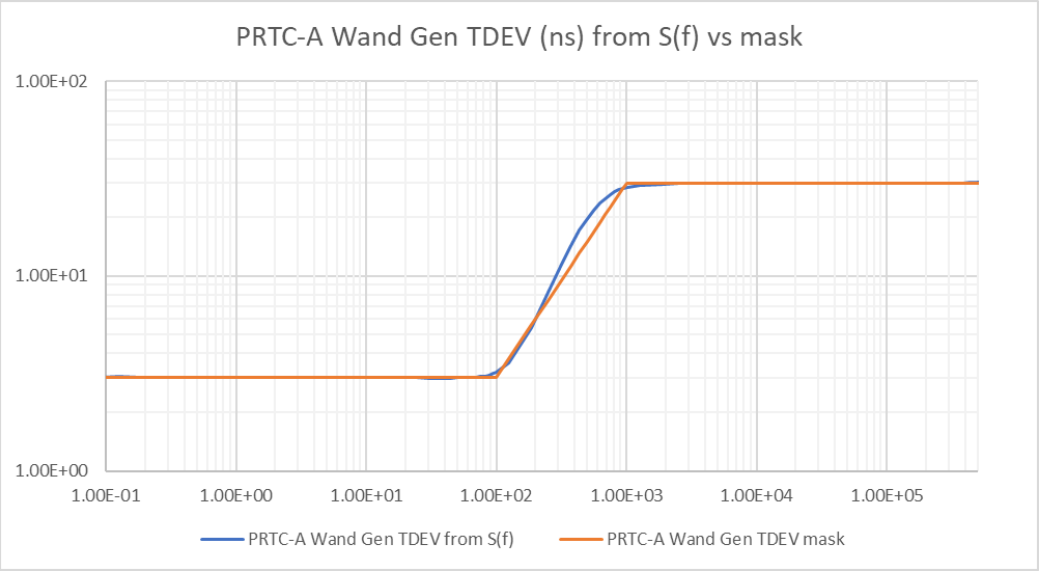
Backup Slides

Additional Simulation Results

PRTC-A Wander Generation TDEV Mask

$$S_x(f) = \left(\frac{G}{f} \cdot (a_1 \cdot H_1(f) + a_2 \cdot H_2(f))\right) \cdot C(f)$$

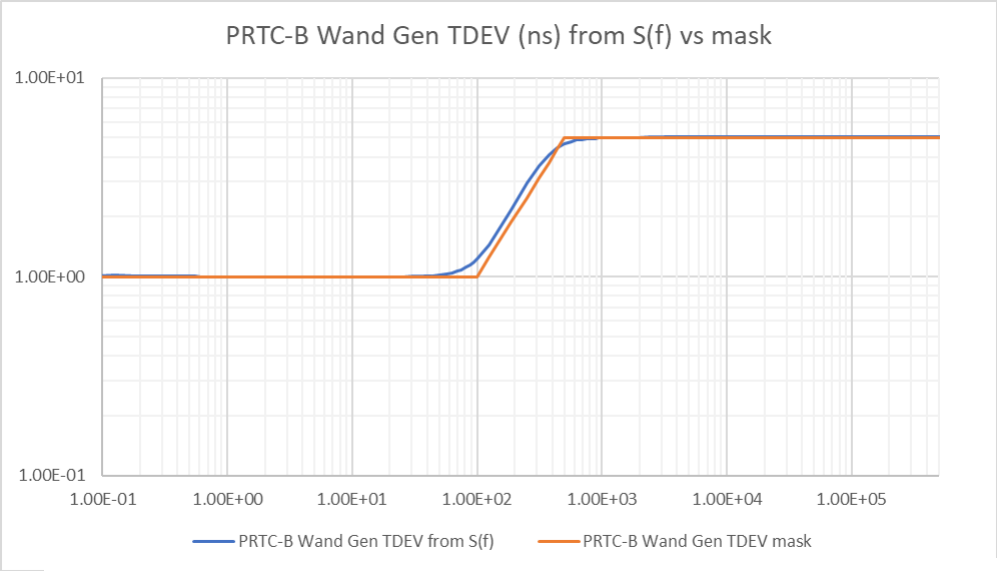
- $H_1(f)$ is a 2nd-order high-pass filter with 3-dB frequency of ~0.002Hz and $a_1 = 3.0^2$;
- $H_2(f)$ is a 3rd-order low-pass filter with 3-dB frequency of ~0.0007Hz and $a_2 = 30.0^2$;
- G ~0.44.



PRTC-B Wander Generation TDEV Mask

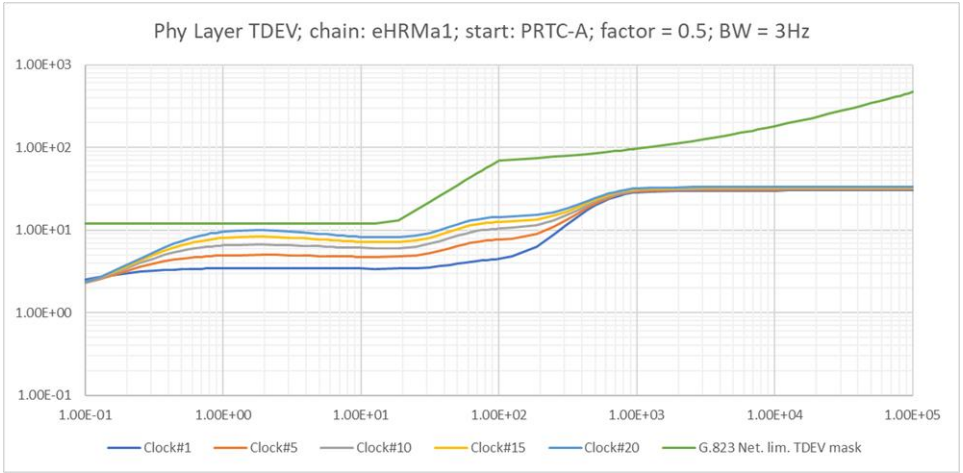
$$S_x(f) = \left(\frac{G}{f} \cdot (a_1 \cdot H_1(f) + a_2 \cdot H_2(f))\right) \cdot C(f)$$

- $H_1(f)$ is a 2nd-order high-pass filter with 3-dB frequency of ~0.001Hz and $a_1 = 1.0^2$;
- $H_2(f)$ is a 3rd-order low-pass filter with 3-dB frequency of ~0.0012Hz and $a_2 = 5.05^2$;
- G ~0.44.



Physical Layer Clock(s): eHRMa1 (start-of-chain PRTC-A)

Phy Layer TDEV (Clock#20 is at end of chain)



- One case shown: scale-factor = 0.5; BW = 3Hz; results available for cases where scale-factor = 0.3535 and 0.19.
- G.8261/G.813 network limit can be met with scale-factor = 0.5; smaller scale-factors provide more margin.

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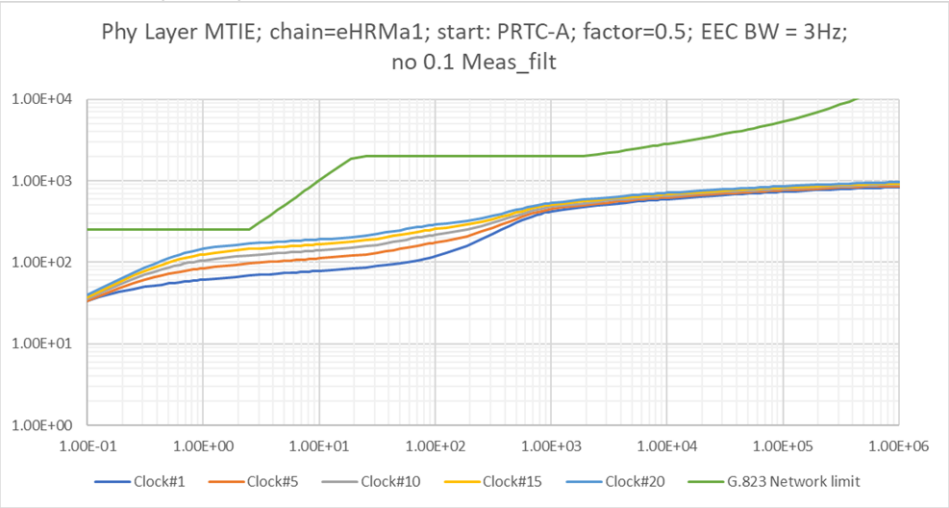
Physical Layer Clock(s): eHRMa1 (start-of-chain = PRTC-A)

Phy Layer MTIE (Clock#20 is at end of chain)



- One case shown: scale-factor = 0.5; BW = 3Hz; results available for cases where scale-factor = 0.3535 and 0.19.
- Compared with time-domain method the frequency domain approach is conservative (factor of ~1.3).
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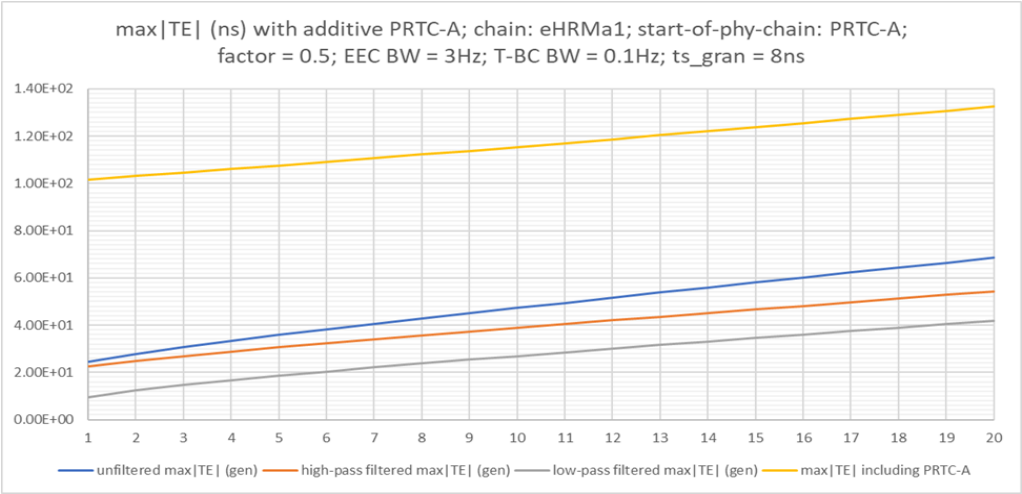
Packet Layer Clock(s): eHRMa1 (start-of-chain = PRTC-A)

Packet Layer Max|TE| (Clock#20 is at end of chain)



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- Max|TE| at clock output obtained by starting chain time-layer with noise-free PRTC and adding in the effect of the PRTC-A at each clock to the filtered time error. The addition is done incoherently.

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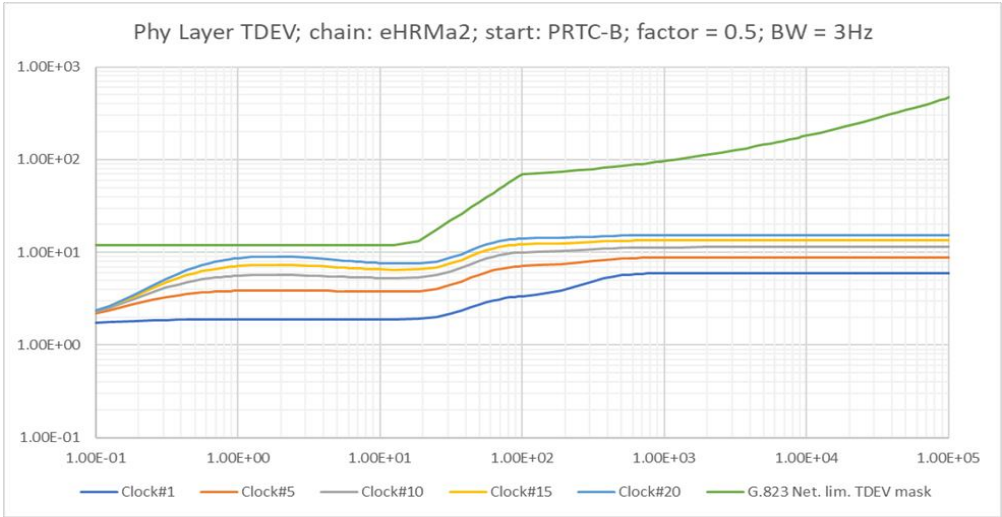
Physical Layer Clock(s): eHRMa2 (start-of-chain PRTC-B)

Phy Layer TDEV (Clock#20 is at end of chain)



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- G.8261/G.813 network limit can be met with scale-factor = 0.5; smaller scale-factors provide more margin.

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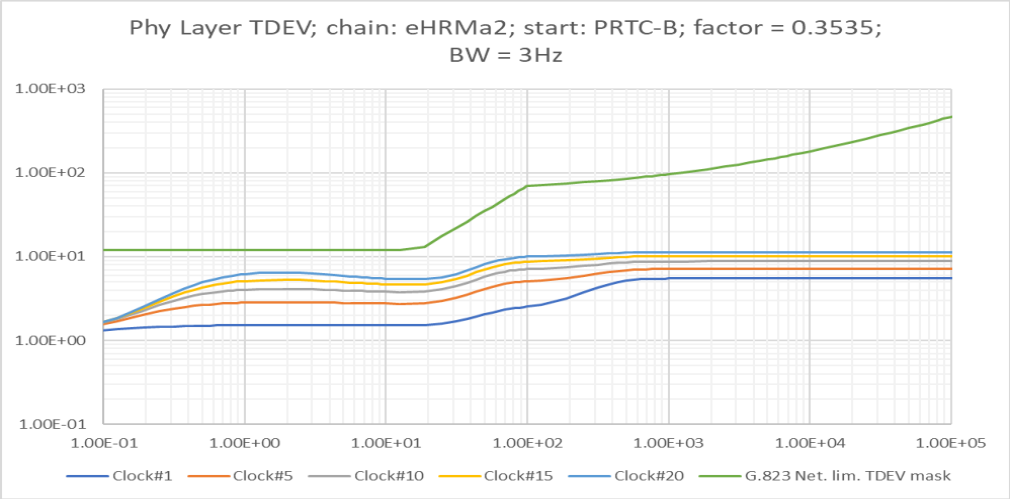
Physical Layer Clock(s): eHRMa2 (start-of-chain = PRTC-B)

Phy Layer MTIE (Clock#20 is at end of chain)



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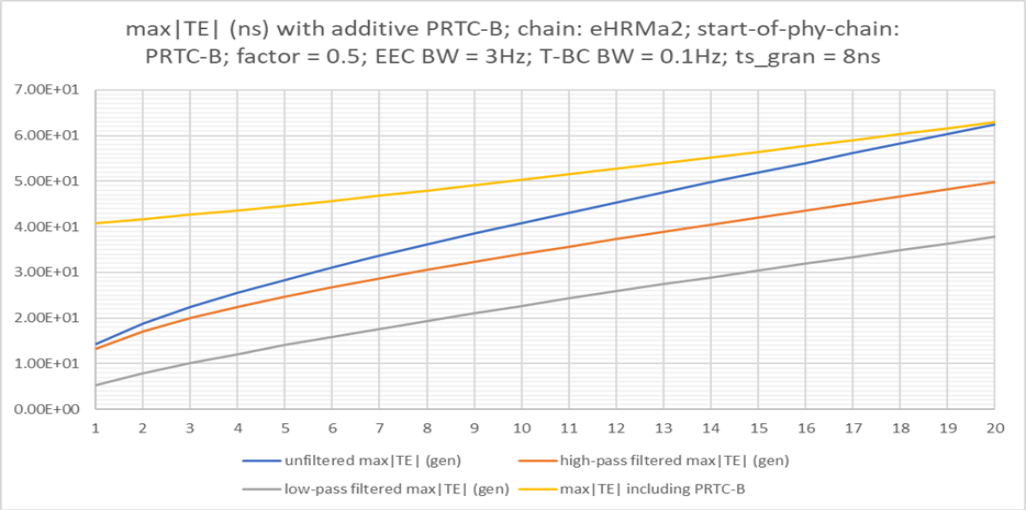
Packet Layer Clock(s): eHRMa2 (start-of-chain = PRTC-B)

Packet Layer Max|TE| (Clock#20 is at end of chain)



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- Compared with time-domain method the frequency domain approach is conservative (uses a peak-to-rms ratio of 8).
- Max|TE| at clock output obtained by starting chain time-layer with noise-free PRTC and adding in the effect of the PRTC-B at each clock to the filtered time error. The addition is done incoherently.

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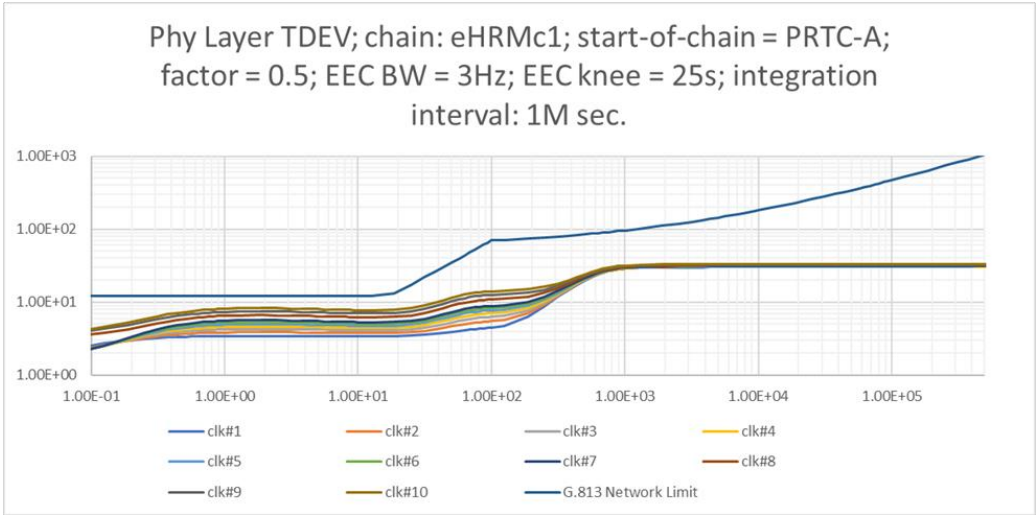
Physical Layer Clock(s): eHRMc1 (start-of-chain PRTC-A)

Phy Layer TDEV (Clock#10 is at end of chain)



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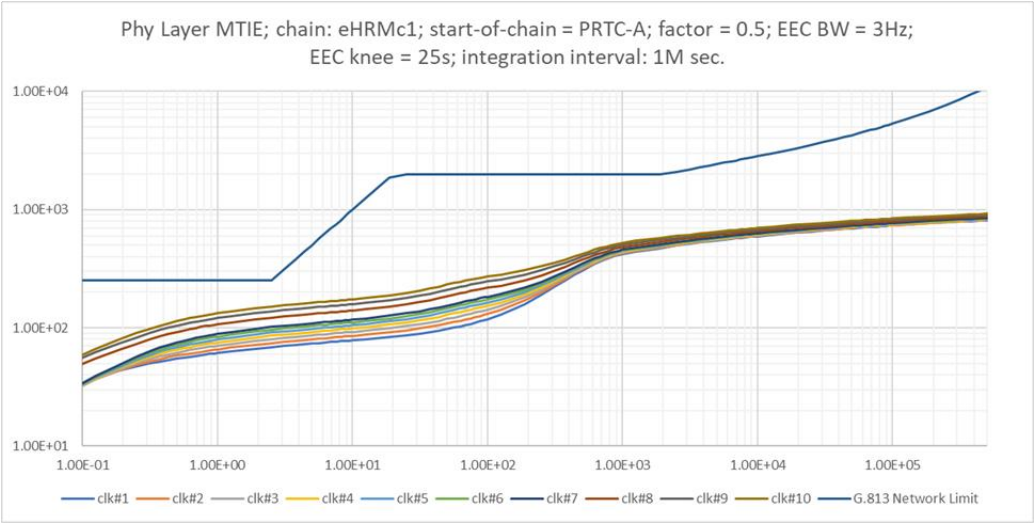

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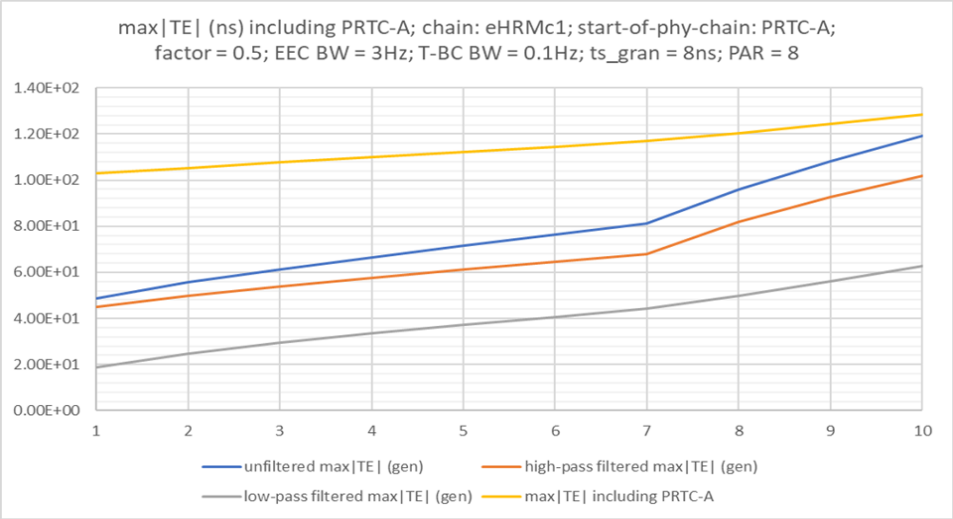
Packet Layer Clock(s): eHRMc1 (start-of-chain = PRTC-A)

Packet Layer Max|TE| (Clock#10 is at end of chain)



- One case shown: scale-factor = 0.5; BW = 3Hz; results available for cases where scale-factor = 0.3535 and 0.19.
- Compared with time-domain method the frequency domain approach is conservative (uses a peak-to-rms ratio of 8).
- Max|TE| at clock output obtained by starting chain time-layer with noise-free PRTC and adding in the effect of the PRTC-A at each clock to the filtered time error. The addition is done incoherently.

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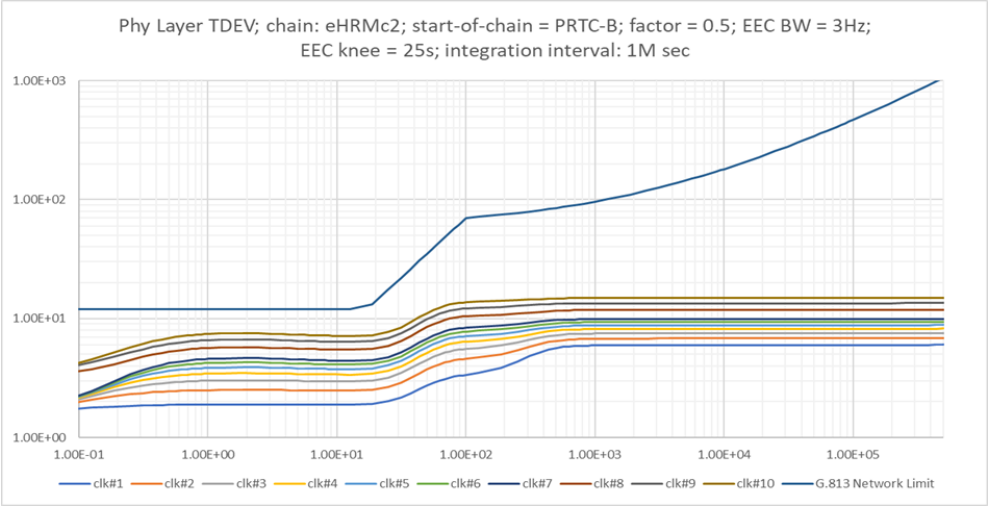
Physical Layer Clock(s): eHRMc2 (start-of-chain PRTC-B)

Phy Layer TDEV (Clock#10 is at end of chain)



- One case shown: scale-factor = 0.5; BW = 3Hz; results available for cases where scale-factor = 0.3535 and 0.19.
- G.8261/G.813 network limit can be met with scale-factor = 0.5; smaller scale-factors provide more margin.

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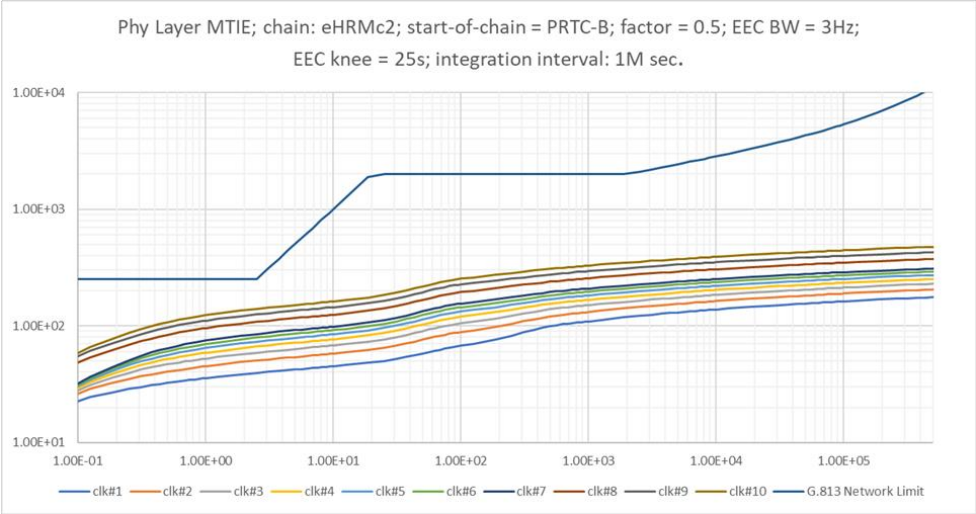
Physical Layer Clock(s): eHRMc2 (start-of-chain = PRTC-B)

Phy Layer MTIE (Clock#10 is at end of chain)



- One case shown: scale-factor = 0.5; BW = 3Hz; results available for cases where scale-factor = 0.3535 and 0.19.
- Compared with time-domain method the frequency domain approach is conservative (factor of ~1.3).
- G.8261/G.813 network limit can be met with scale-factor = 0.5; smaller scale-factors provide more margin.

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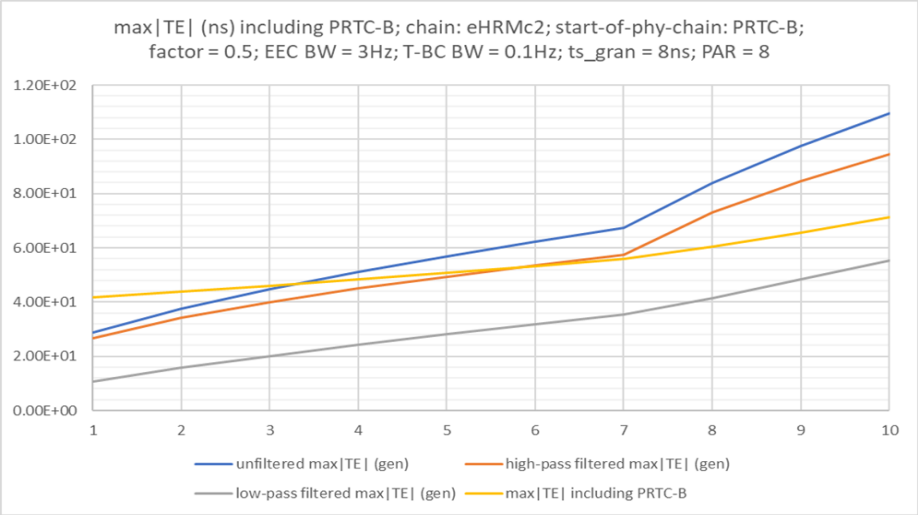
Packet Layer Clock(s): eHRMc2 (start-of-chain = PRTC-A)

Packet Layer Max|TE| (Clock#10 is at end of chain)



- One case shown: scale-factor = 0.5; BW = 3Hz; results available for cases where scale-factor = 0.3535 and 0.19.
- Compared with time-domain method the frequency domain approach is conservative (uses a peak-to-rms ratio of 8).
- Max|TE| at clock output obtained by starting chain time-layer with noise-free PRTC and adding in the effect of the PRTC-B at each clock to the filtered time error. The addition is done incoherently.

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Thank You!

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