# Simulation of a Chain of Clocks

ITSF 2019
Brighton November 2019

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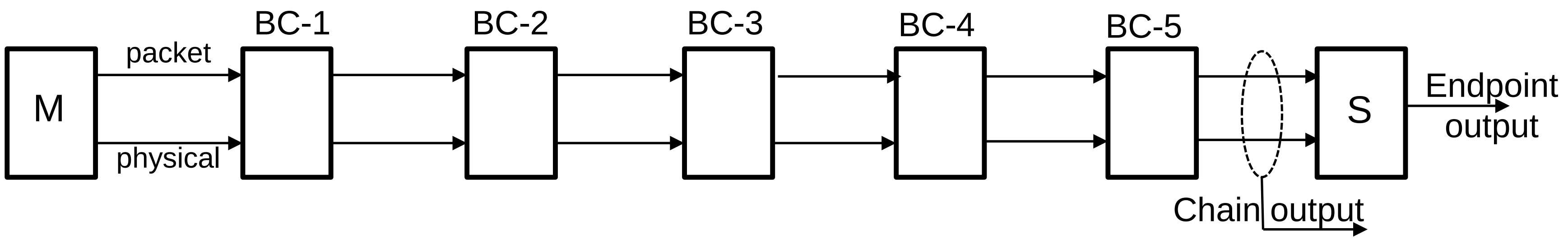
# Outline of Presentation

- Some Background
- Chain of clocks
- Mathematical Model for analysis
- Frequency model for the oscillator
- Analysis of clock error (Phy layer) for chain of 5 T-BCs
- Spectral models appropriate for SEC and eSEC network limit MTIE masks & frequency deviation in endpoint clock when output of chain is at network limit
- Concluding Remarks

# Some Background

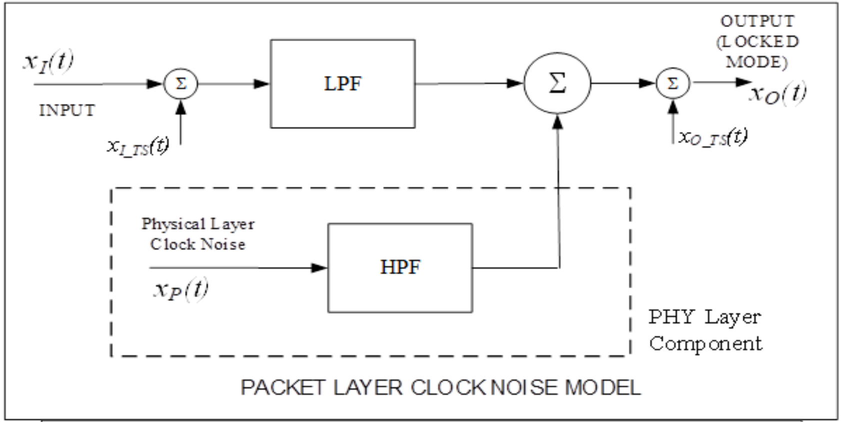
- Motivations for this study:
  - Analyze the timing behavior of a chain of clocks and provide a rapid (not time-consuming) approach to estimate timing behavior
  - The focus of this study is the physical layer chain with emphasis on the end-point (application) clock
- The underlying premise:
  - Analytical approach to evaluation of clock performance in a chain of clocks using a frequency domain approach to estimate standard deviation
  - Other Metrics (MTIE, max|TE|) involving “peak” and “maximum” estimated as G times standard deviation (G is about 4.0 to 8.0) derived from spectrum
  - All noise sources are uncorrelated so that they add in power (variance)
  - **Frequency offsets, constant Time Error (cTE), asymmetry effects, deterministic signals, temperature effects, and time-varying phenomena are not included here**

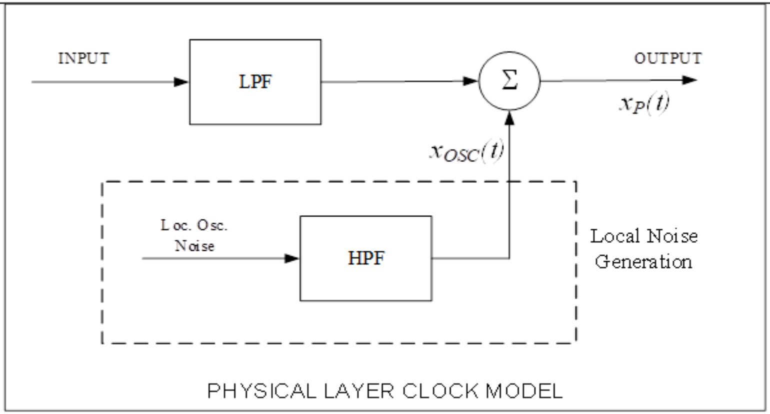
# Chain of clocks (Fronthaul, C-RAN)




- Timing chain for Fronthaul/C-RAN likely to be less than 5 boundary clocks between Master (Edge GrandMaster or BBU) and Slave (Small Cell / RRH)
- The output of the chain must meet the requirements (e.g. TDEV, MTIE) of the physical layer exemplified by the SEC or eSEC network limit
- The end-point (application) clock must meet the application requirements even when the chain output is at the network limit
- In this presentation we consider the physical layer ("SyncE"); the time layer (PTP) is considered separately

# 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*
- Time-stamps T2 and T4 have quantization error (time-stamp granularity).

Focus of this Presentation

- Physical layer clock noise model
- Input of clock n is output of clock (*n*-1)
- Physical layer clock output of clock *n* also goes to time-layer of clock *n*
- Local noise generation modeled as either based on oscillator ***or*** based on noise-generation TDEV mask

Analysis is done in frequency domain



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# Mathematical formulation

Assumed sampling rate $f_0$ = 16Hz; sampling interval $\tau_0$ = 0.0625s

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

TVAR from spectrum

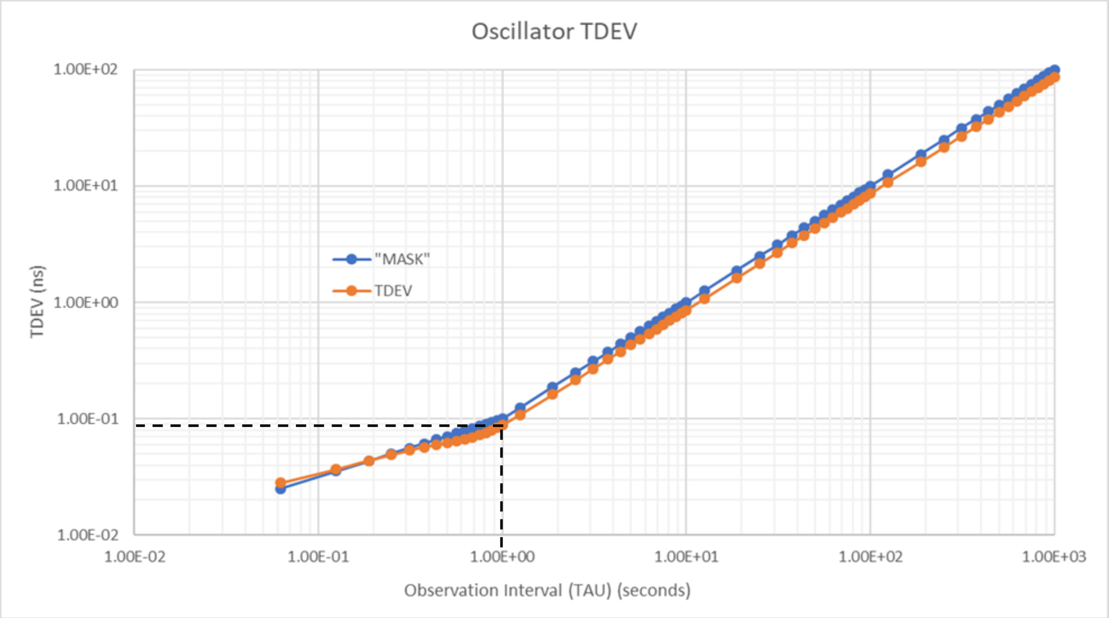
$$\sigma_\xi^2(n) \approx \int_0^{f_0} S_x(f) \cdot 4 \cdot \left(\sin(n\pi f\tau_0)^2\right) df$$

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

MTIE from spectrum
{ maximum = 7 · sigma }

- The calculation of frequency offset as a function of observation interval is a subset of the MTIE calculation
- MTIE calculation includes addressing the non-decreasing nature of MTIE

# Oscillator Model




- Mixture of white FM (low tau) and flicker FM (larger tau)
- “knee” is the cross-over point, assumed to be 1s here
- Oscillator quality represented by TDEV($\tau$ = knee)
- “Mask” = straight line view
- TDEV for very low observation intervals (<< knee) represents phase-noise (not considered here)
- Oscillator spectrum constructed as low-pass-filtered flicker FM and high-pass filtered white FM and resulting TDEV shown

Note: white FM TDEV follows $\tau^{0.5}$; flicker FM TDEV follows $\tau^{1.0}$; range of $\tau$ considered is small enough to ignore higher order noise types.

Assumption: TDEV(@1s) = 0.1ns



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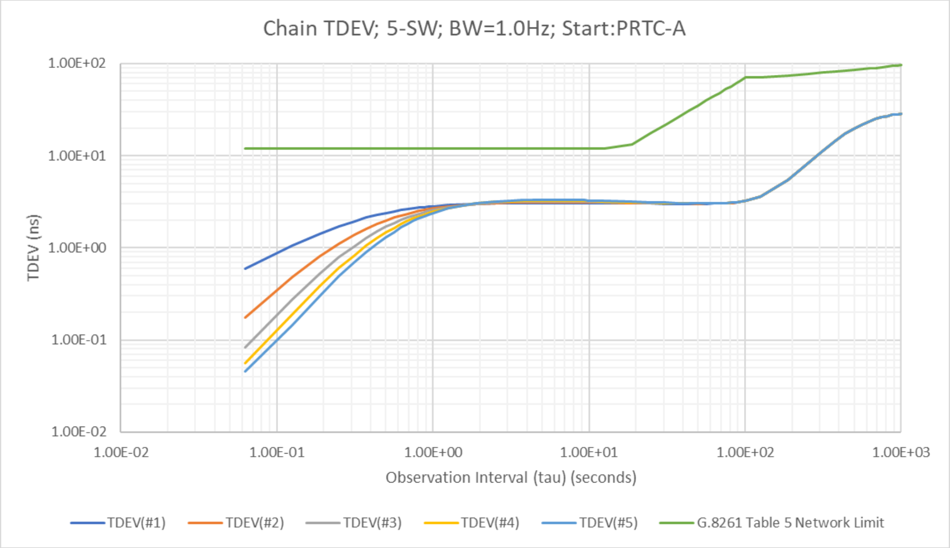
# Chain output Phy_Layer - TDEV




Note: Principal source of clock noise is the starting point (PRTC-A)

- Expected TDEV of clock chain (5 T-BC) (phy_layer) using oscillator with assumed performance (TDEV(@1s) = 0.1ns) for clock bandwidth of 1.0Hz
- Start-of-chain is PRTC-A (equivalent of G.811 for phy_layer)
- Mask is the network limit for Synchronous Ethernet (see G.8261 Table 5)
- Cases with other bandwidths provided in back-up



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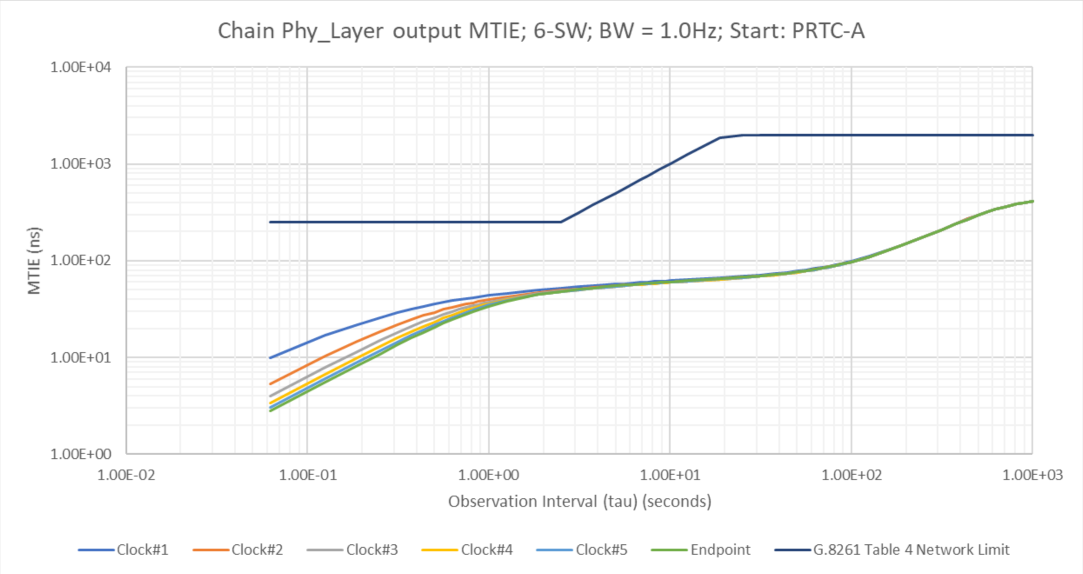
# Chain output Phy_Layer - MTIE




Note: This simulation used the same bandwidth for all clocks – chain as well as endpoint.

- Expected MTIE of clock chain (phy_layer) (including endpoint) using oscillator with assumed performance (TDEV(@1s) = 0.1ns) for bandwidth of 1.0Hz
- Start-of-chain is PRTC-A (equivalent of G.811 for phy_layer)
- Mask is the network limit for Synchronous Ethernet (see G.8261 Table 4)
- Cases with other bandwidths provided in back-up



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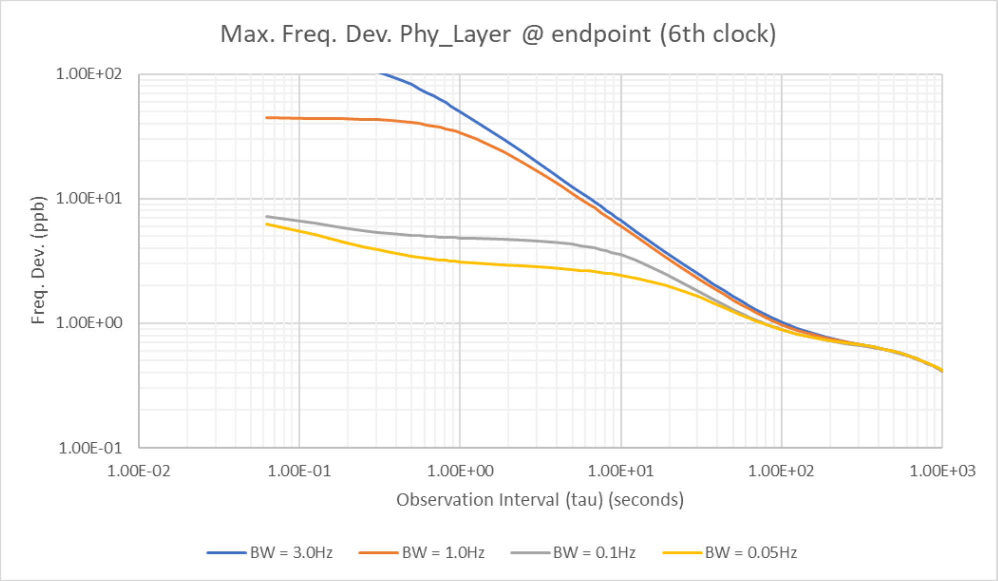
# Max. Freq. Deviation (Phy_Layer) - Endpoint




Note: This simulation used the same bandwidth for all clocks – chain as well as endpoint.

- Expected maximum frequency deviation (phy_layer) as a function of observation interval for various bandwidths (using oscillator with TDEV(@1s) = 0.1ns)
- Start-of-chain is PRTC-A (equivalent of G.811 for phy_layer)
- Common requirement is "better than 16ppb"
- Phy_layer clock often used to generate RF carrier in end-point (e.g. RRH)



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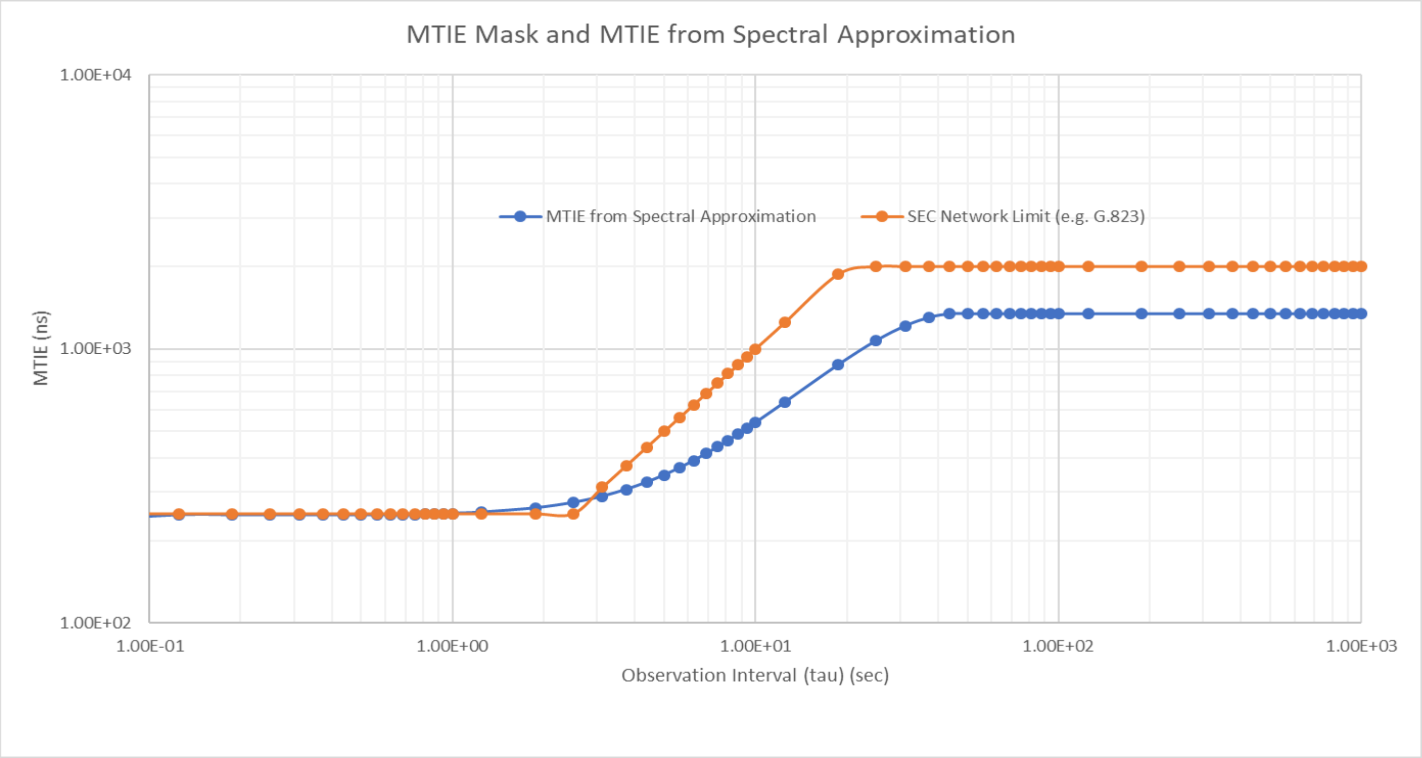
# Spectral Model Matching SEC MTIE Network Limit




- Not possible to find a suitable *S(f)* that yields a perfect MTIE match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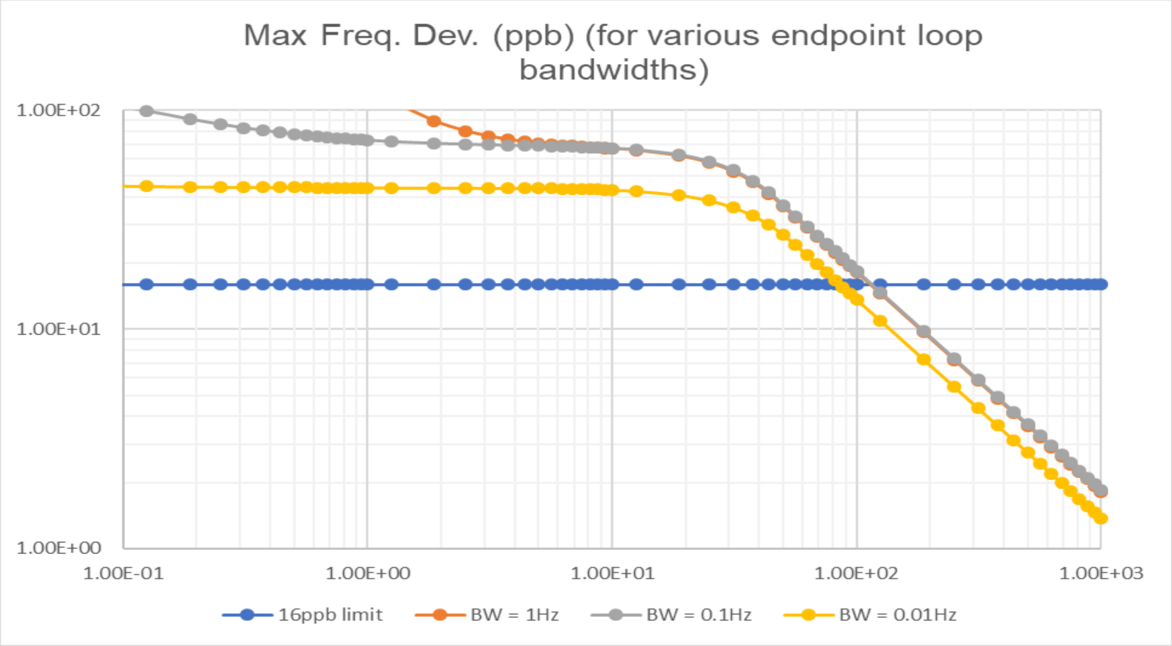
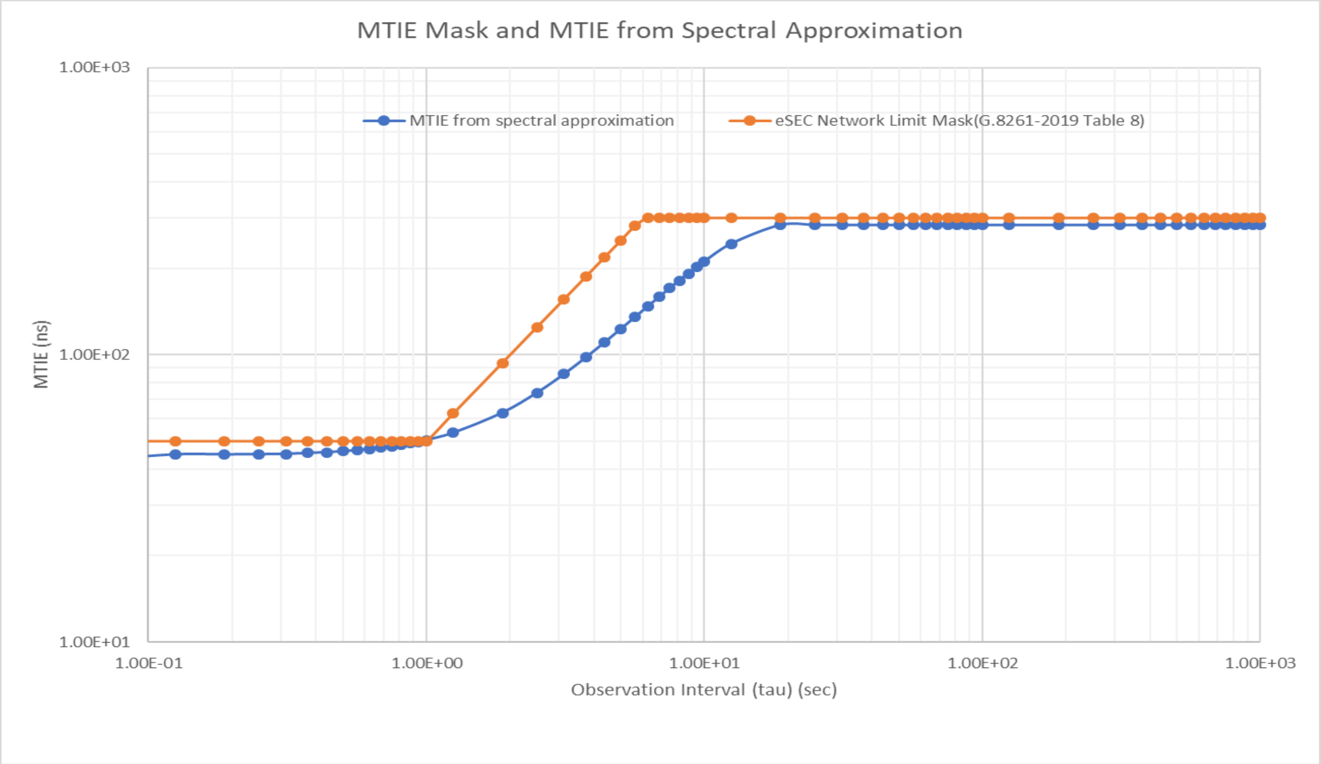
# Max. Freq. Deviation (Phy_Layer) - Endpoint



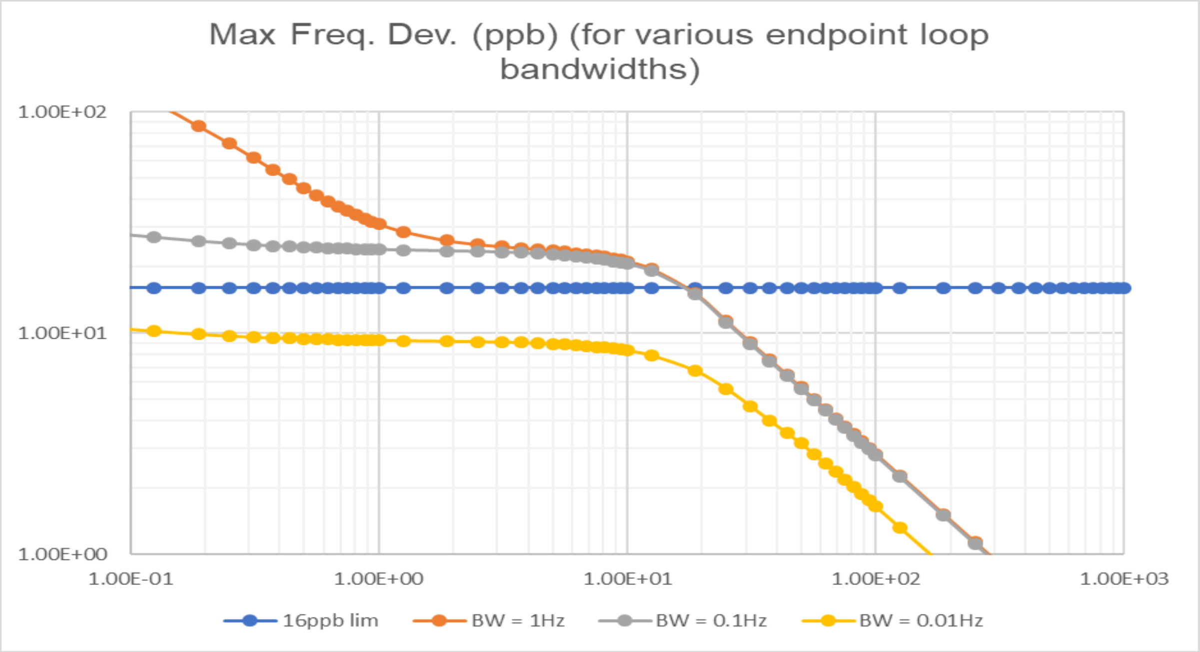

- Expected maximum frequency deviation (phy_layer) as a function of observation interval for various bandwidths (using oscillator with TDEV(@1s) = 0.1ns)
- Input to Endpoint set to regular SEC Mask (approximation)

# Spectral Model Matching eSEC MTIE Network Limit




- Not possible to find a suitable *S(f)* that yields a perfect MTIE match

# Max. Freq. Deviation (Phy_Layer) - Endpoint




- Expected maximum frequency deviation (phy_layer) as a function of observation interval for various bandwidths (using oscillator with TDEV(@1s) = 0.1ns)
- Input to Endpoint set to enhanced SEC Mask (approximation)



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# Concluding Remarks

- The results described here used the frequency-domain method.
  - The frequency-domain method is computationally rapid and can provide results quickly, allowing analysis of several “what if?” scenarios in a timely fashion but cannot handle time-varying phenomenon
- A suitable model for an oscillator (random noise viewpoint):
  - Preferably involves 2 parameters:
    - “knee” : observation interval corresponding to cross-over between white FM and flicker FM
    - TDEV(@ $\tau$ = “knee”)
  - A single parameter, namely TDEV( $\tau$ = “knee” = 1s), may be adequate if actual knee > 1s.
- The method permits an analysis of the trade-offs between bandwidth and performance metrics
  - Example: to meet the maximum frequency deviation of 16ppb at the endpoint, for a chain starting with a G.811 quality clock, a bandwidth of the order of 0.05Hz is recommended
  - Example: when the input to the endpoint clock is at the regular SEC network limit, the 16ppb limit is achievable for observation intervals greater than 100s for various bandwidths.
  - Example: when the input is at the enhanced SEC network limit, the 16ppb limit is met for all observation intervals with a bandwidth of 0.01Hz.

# Questions?

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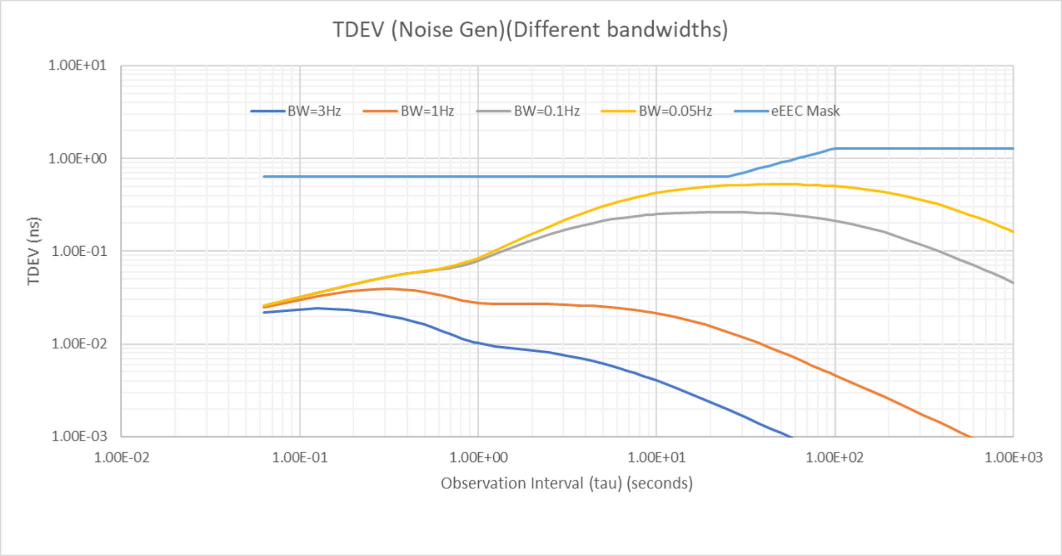
# Backup Slides

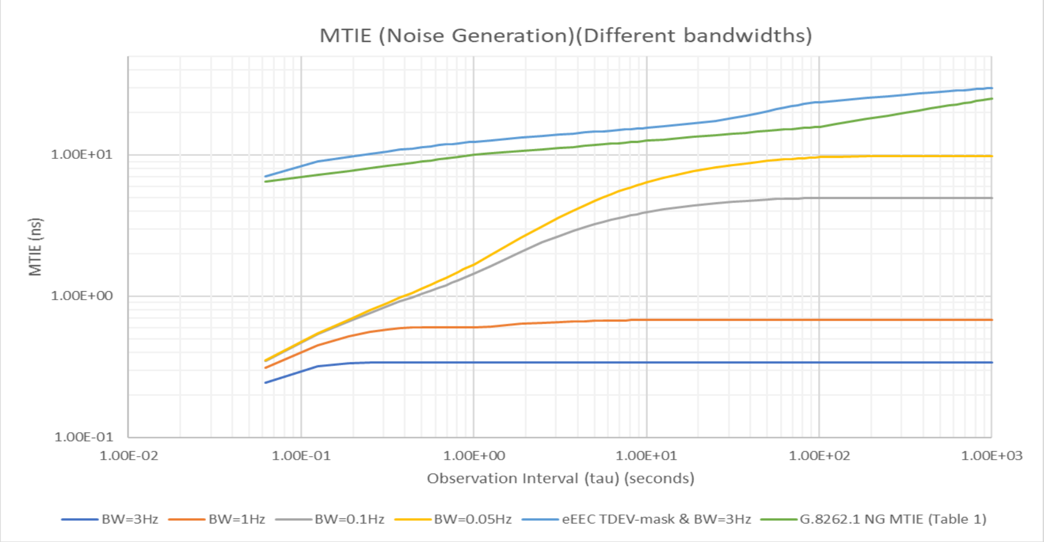
Additional Simulation Results

# Phy_Layer Noise Generation - TDEV




- Expected noise generation of phy_layer clock using oscillator with assumed performance for various bandwidths
- Enhanced EEC bandwidth is specified as between 1Hz and 3Hz
- With this oscillator even bandwidth as low as 0.05Hz is compliant

# Phy_Layer Noise Generation - MTIE



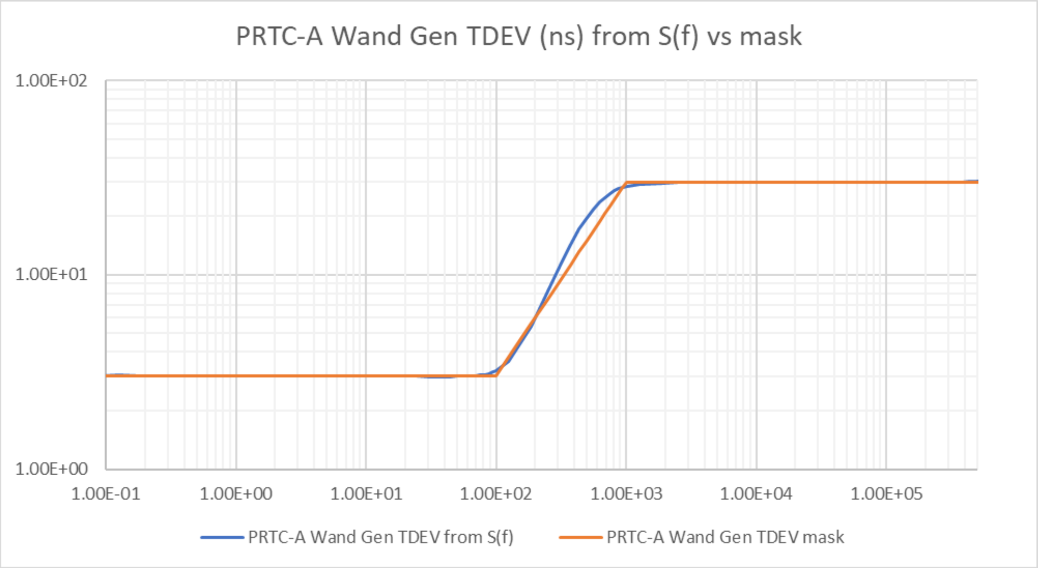

Note: Even if the clock noise generation satisfies the required TDEV (mask) it could violate the required MTIE mask, even with the widest bandwidth (3Hz). This is a known effect.
Note: MTIE calculation here is conservative.

- Expected noise generation of phy_layer clock using oscillator with assumed performance for various bandwidths
- Enhanced EEC bandwidth is specified as between 1Hz and 3Hz
- With this oscillator even bandwidth as low as 0.05Hz is compliant

# 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.



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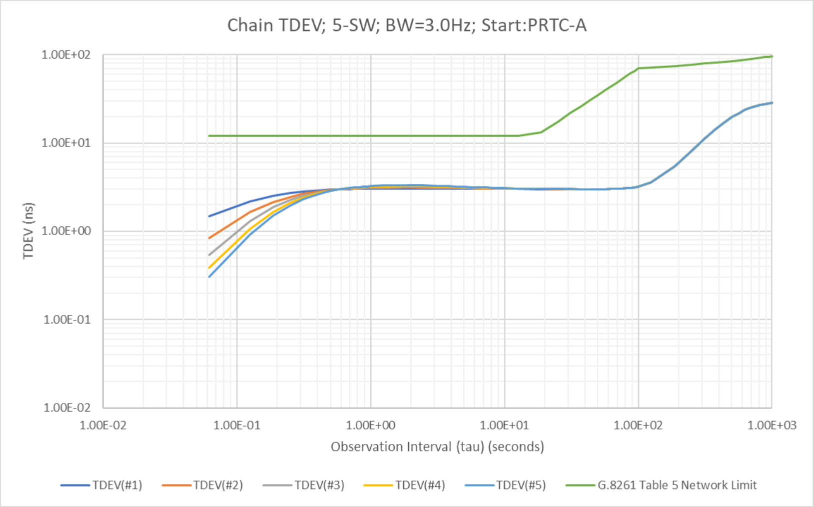
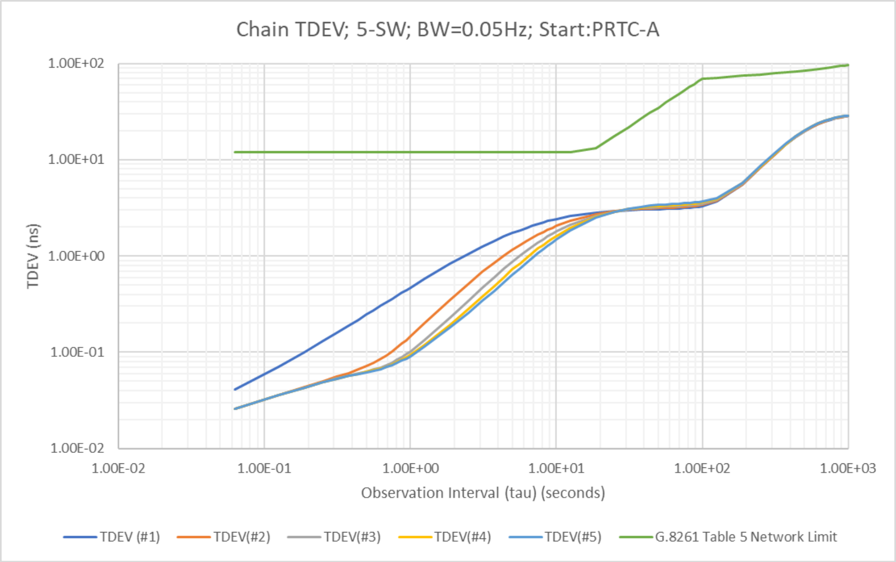
# Chain output Phy_Layer - TDEV



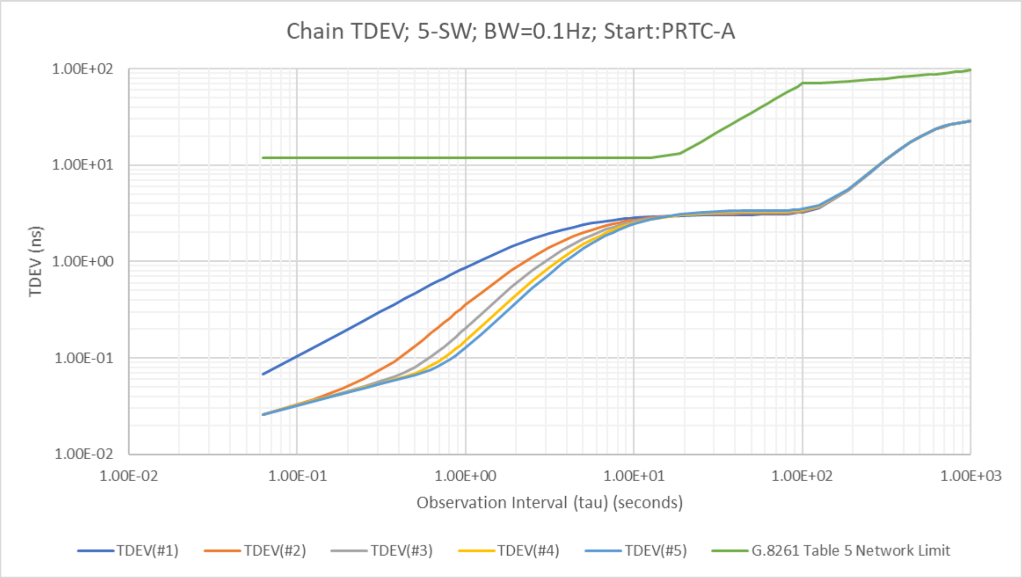

- Expected TDEV of clock chain (phy_layer) using oscillator with assumed performance for bandwidth of 3.0Hz [Earlier results used a “worst case” where the noise-generation mask was used rather than oscillator performance]
- Start-of-chain is PRTC-A (equivalent of G.811 for phy_layer)
- Mask is the network limit for Synchronous Ethernet (see G.8261 Table 5)

# Chain output Phy_Layer - TDEV




- Expected TDEV of clock chain (phy_layer) using oscillator with assumed performance for bandwidth of 0.05Hz
- Start-of-chain is PRTC-A (equivalent of G.811 for phy_layer)
- Mask is the network limit for Synchronous Ethernet (see G.8261 Table 5)

# Chain output Phy_Layer - TDEV




- Expected TDEV of clock chain (phy_layer) using oscillator with assumed performance for bandwidth of 0.1Hz
- Start-of-chain is PRTC-A (equivalent of G.811 for phy_layer)
- Mask is the network limit for Synchronous Ethernet (see G.8261 Table 5)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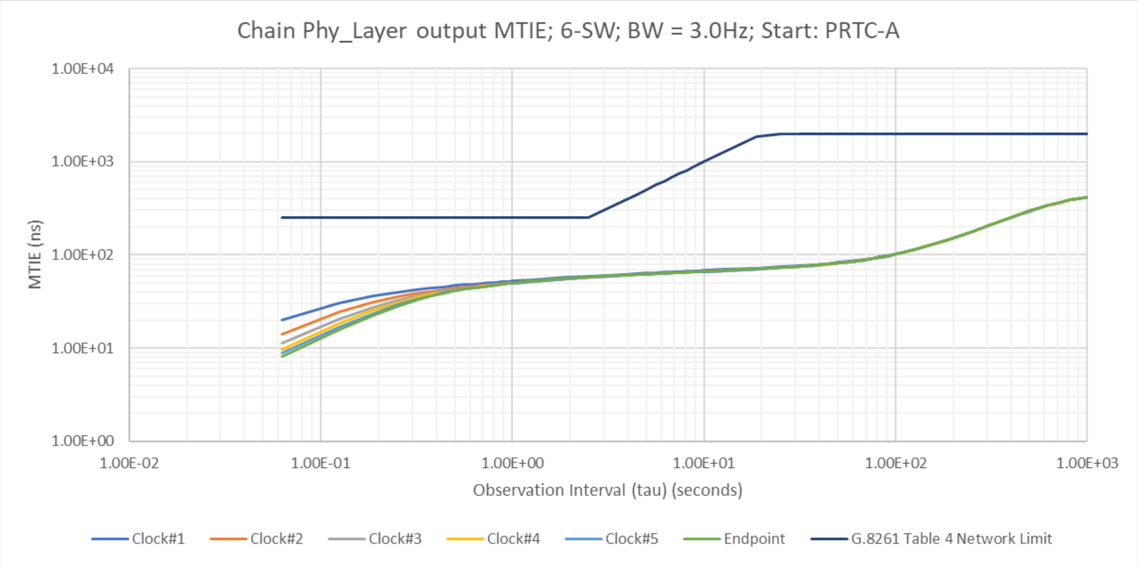
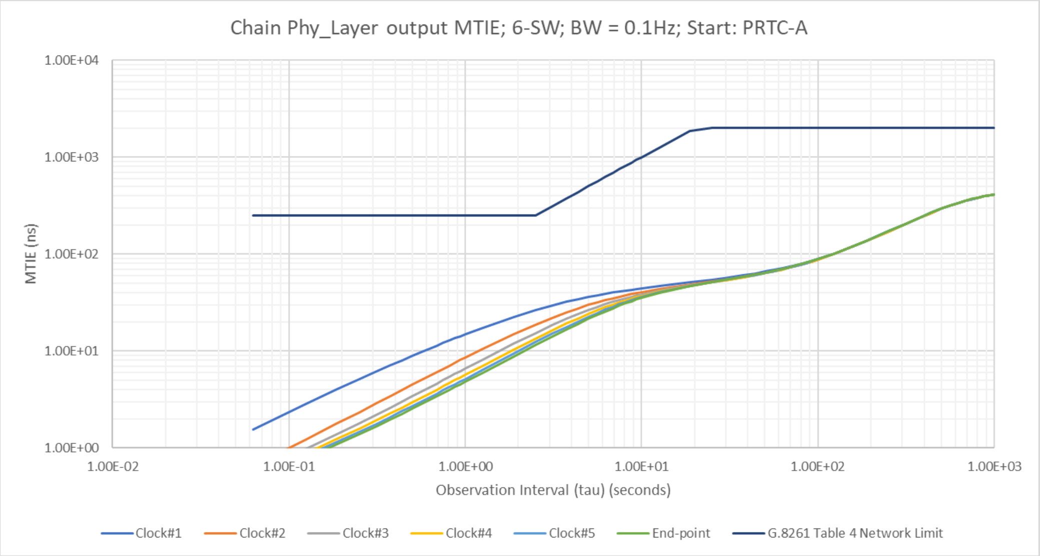
# Chain output Phy_Layer - MTIE



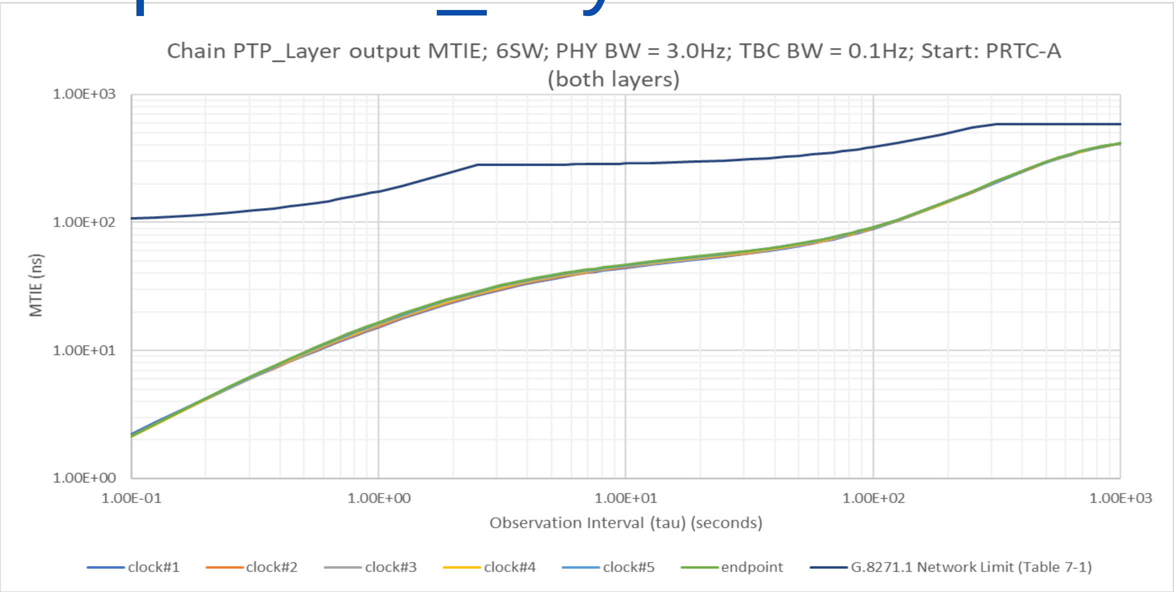

- Expected MTIE of clock chain (phy_layer) using oscillator with assumed performance for bandwidth of 3.0Hz [Earlier results used a “worst case” where the noise-generation mask was used rather than oscillator performance]
- Start-of-chain is PRTC-A (equivalent of G.811 for phy_layer)
- Mask is the network limit for Synchronous Ethernet (see G.8261 Table 4)

# Chain output Phy_Layer - MTIE



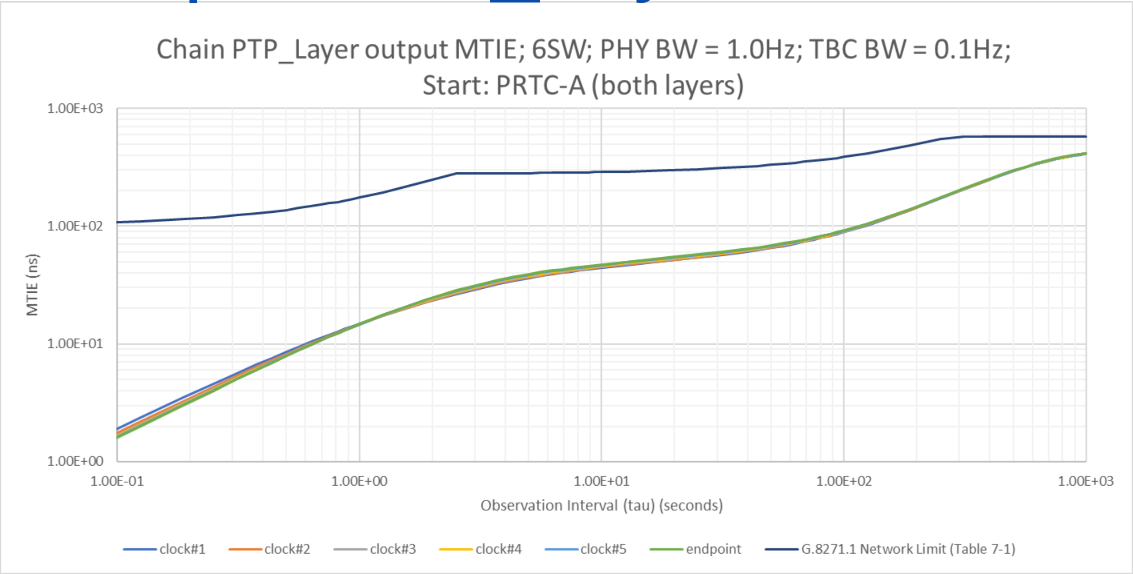

- Expected MTIE of clock chain (phy_layer) using oscillator with assumed performance for bandwidth of 0.1Hz
- Start-of-chain is PRTC-A (equivalent of G.811 for phy_layer)
- Mask is the network limit for Synchronous Ethernet (see G.8261 Table 4)

# Chain output PTP_Layer - MTIE



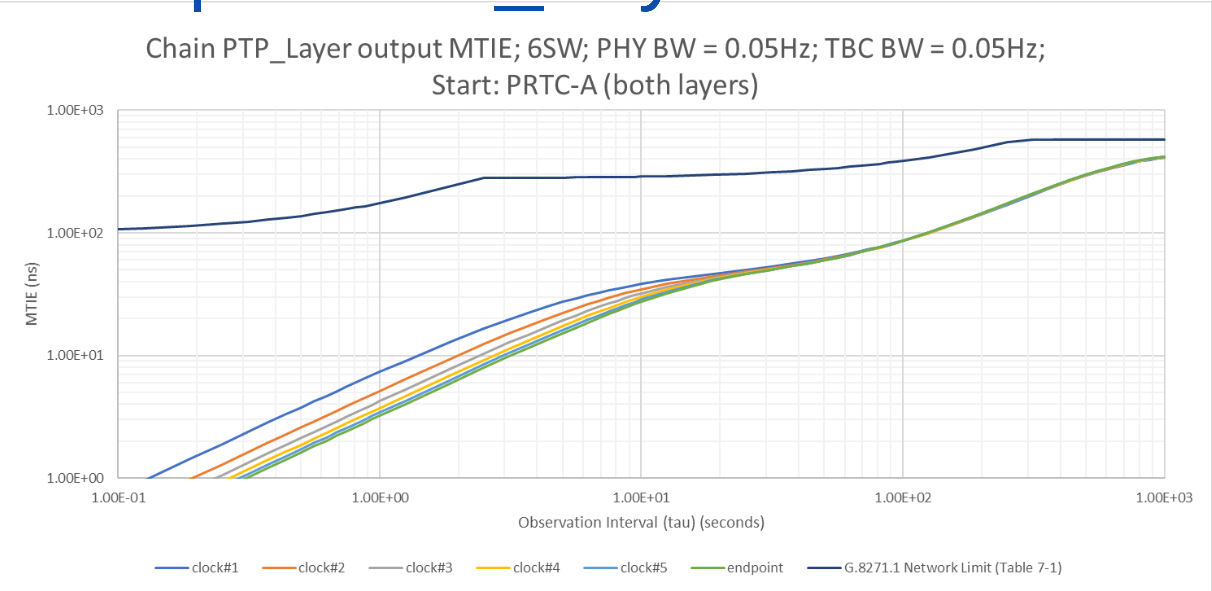

- Expected MTIE of clock chain (PTP_layer) (including endpoint) using oscillator with assumed performance (TDEV(@1s) = 0.1ns) for phy_layer bandwidth of 3.0Hz and PTP_layer bandwidth of 0.1Hz
- Start-of-chain is PRTC-A for both phy_layer and PTP_layer
- Mask is the network limit from G.8271.1 (Table 7-1)
- Time-stamp granularity of 8ns

# Chain output PTP_Layer - MTIE




- Expected MTIE of clock chain (PTP_layer) (including endpoint) using oscillator with assumed performance (TDEV(@1s) = 0.1ns) for phy_layer bandwidth of 1.0Hz and PTP_layer bandwidth of 0.1Hz
- Start-of-chain is PRTC-A for both phy_layer and PTP_layer
- Mask is the network limit from G.8271.1 (Table 7-1)
- Time-stamp granularity of 8ns

# Chain output PTP_Layer - MTIE




- Expected MTIE of clock chain (PTP_layer) (including endpoint) using oscillator with assumed performance (TDEV(@1s) = 0.1ns) for phy_layer bandwidth of 0.05Hz and PTP_layer bandwidth of 0.05Hz
- Start-of-chain is PRTC-A for both phy_layer and PTP_layer
- Mask is the network limit from G.8271.1 (Table 7-1)
- Time-stamp granularity of 8ns



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# Chain Time Error Accumulation

- To see accumulation of time error generated by the chain, the starting point (PRTC-A/T-GM) introduces only time-stamping error
- Physical Layer starts with PRTC-A (essentially G.811) at its limit (TDEV mask)
- Time error estimated with 0.1Hz measurement filter
- Time-stamp granularity assumed to be 8ns
- 4 cases considered with different choices of filter bandwidths

| | **Phy_layer bandwidth** | **PTP_layer bandwidth** |
|---|---|---|
| Case #1 | 3.0 Hz | 0.1 Hz |
| Case #2 | 1.0 Hz | 0.1 Hz |
| Case #3 | 0.1 Hz | 0.1 Hz |
| Case #4 | 0.05 Hz | 0.05 Hz |



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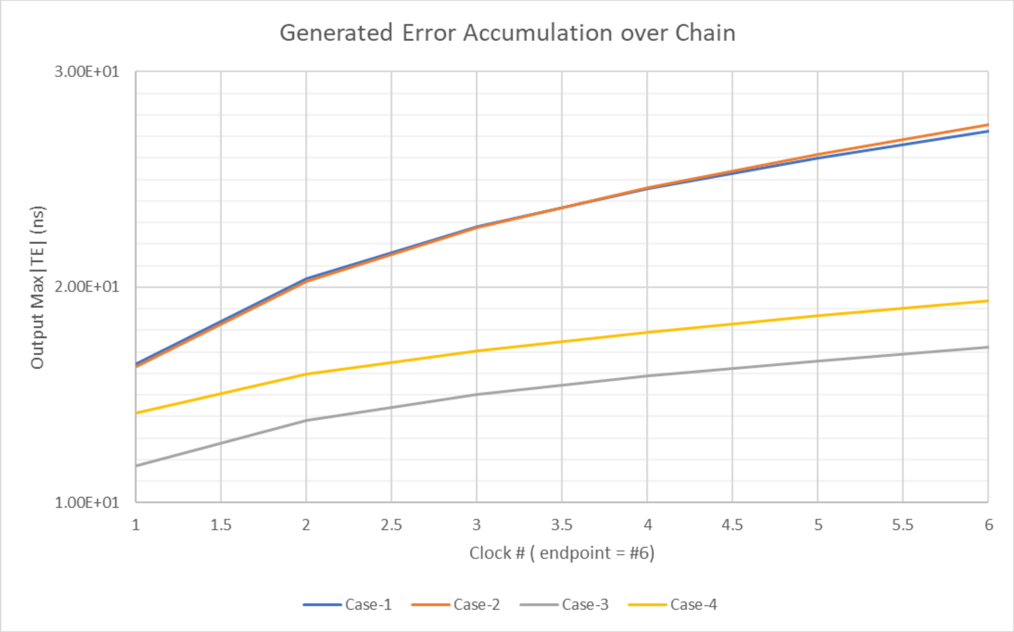
# Chain Time Error Accumulation




- Error accumulation shows an interaction between choices of bandwidth
  - Case #3 has 0.1Hz bandwidth for both layers
- The optimal choice of bandwidths will depend on assumed oscillator performance



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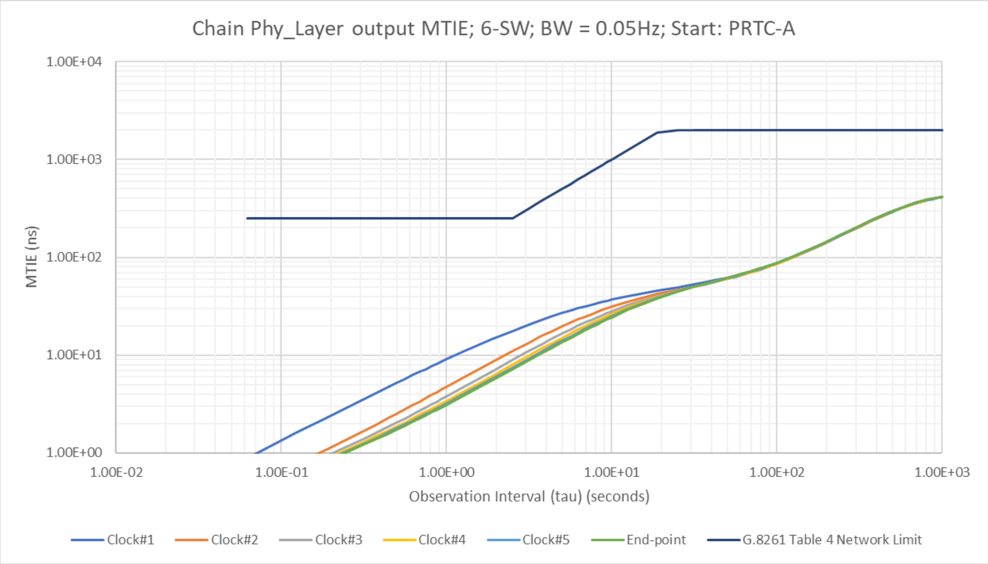
# Chain output Phy_Layer - MTIE



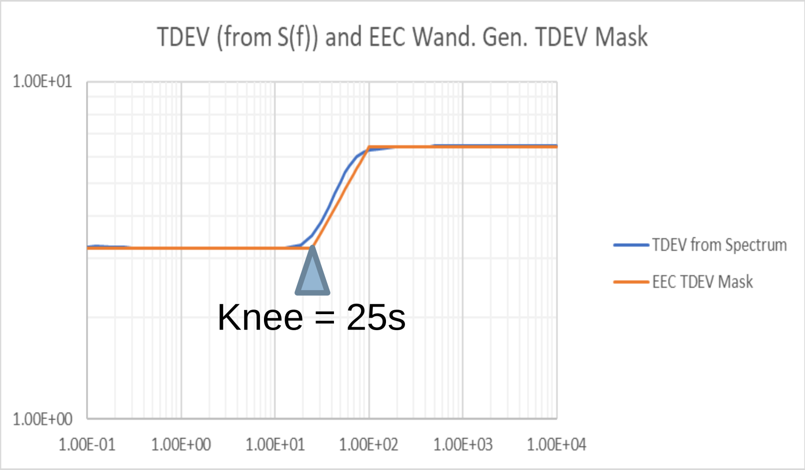

- Expected MTIE of clock chain (phy_layer) using oscillator with assumed performance for bandwidth of 0.1Hz
- Start-of-chain is PRTC-A (equivalent of G.811 for phy_layer)
- Mask is the network limit for Synchronous Ethernet (see G.8261 Table 4)

# 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* = $\alpha$

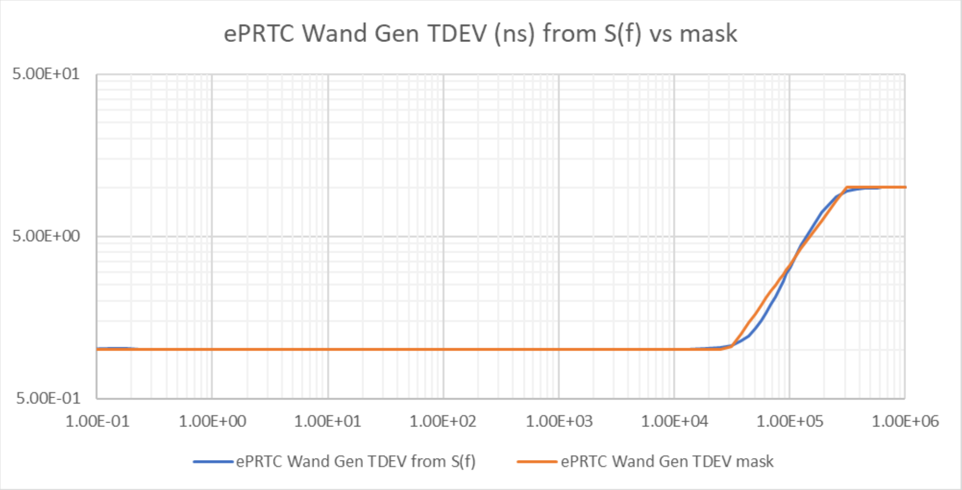
In G.8262.1 (eEEC) the appropriate factor is ~0.2

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

# 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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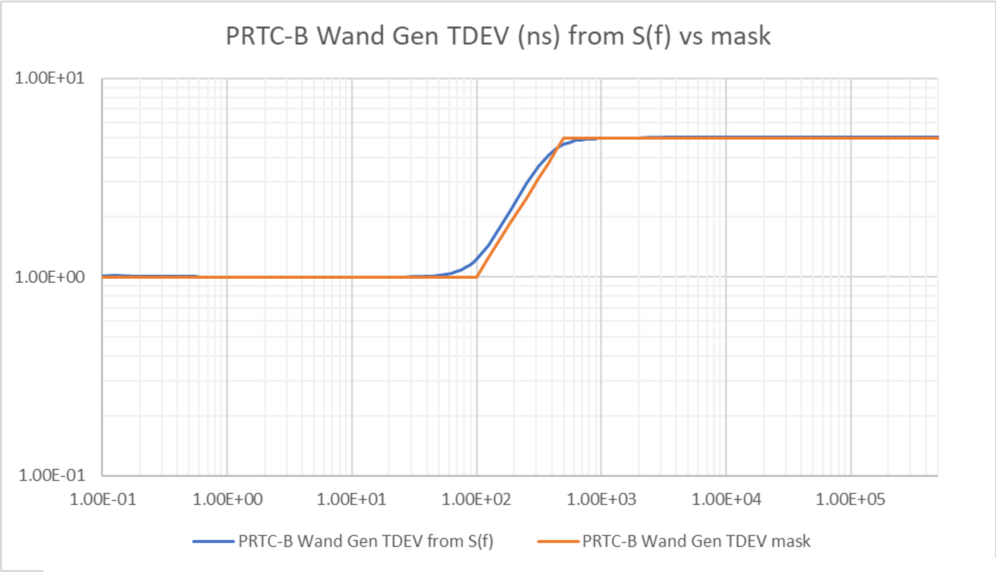
# PRTC-B Wander Generation TDEV Mask

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

- $H_1(f)$ 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.



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# Thank You!

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