Endpoint Clocks

WSTS-2025

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Presentation Outline

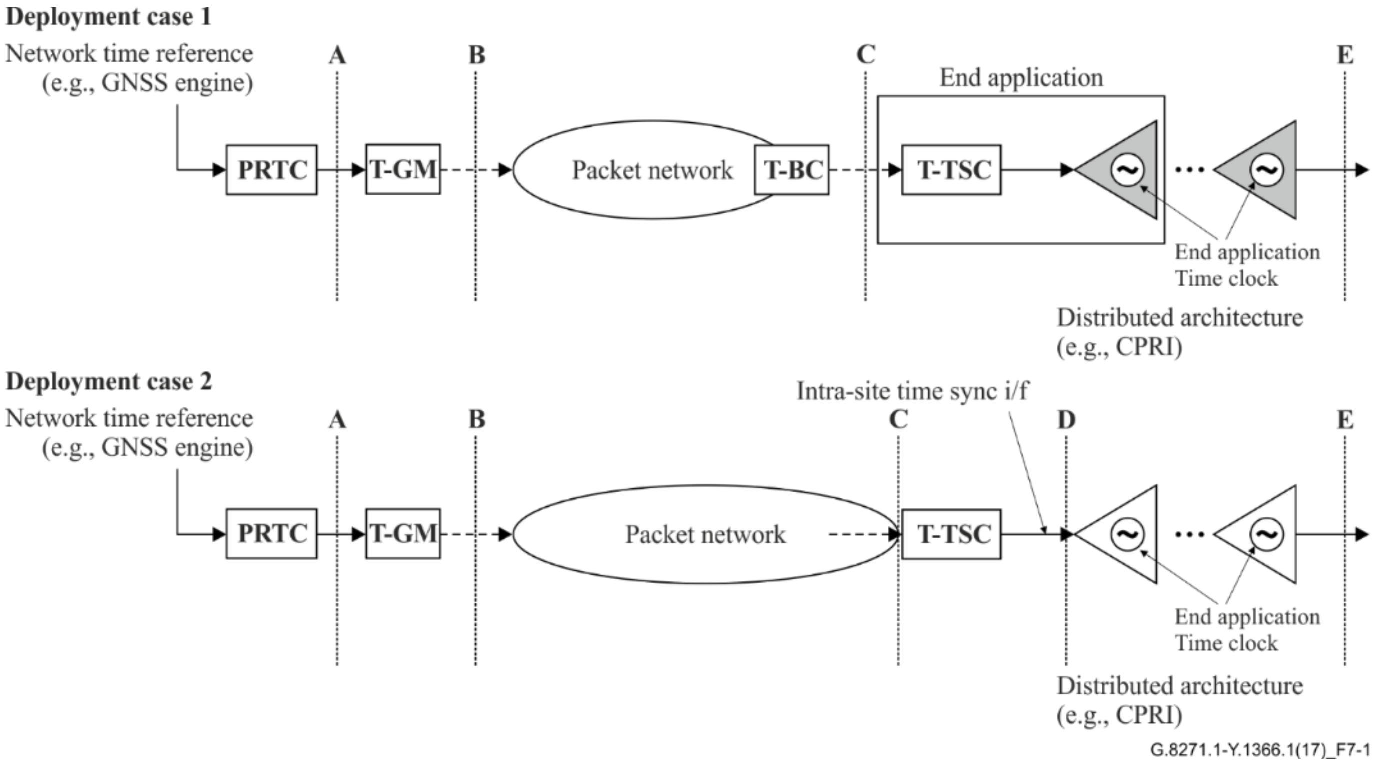
The Premise:

- Endpoint clocks are those at the very edge of the network and are responsible for providing timing accuracy and stability as prescribed by the application.
- There are multiple interacting design choices that must be made.
- An analytical framework that provides rapid results, albeit approximate, can serve as a good starting point for more detailed studies.

Presentation Outline:

- Role of Endpoint Clocks as exemplified by Wireless Radio Units (RUs)
- Analytical Model for noise accumulation in the Front Haul Network
- Endpoint Clock Time Error Variance Estimation
- Example Calculations and Analyses
- Spectral Models for Oscillators and the Enhanced Synchronous Ethernet Interface [In Back-Up slides]

Wireless RU Timing



From G.8271.1

- G.8271.1 Deployment Cases:
  - G.8271.1 Deployment Case 1: Endpoint T-TSC is integrated into end application
  - G.8271.1 Deployment Case 2: Endpoint *TimeReceiver* Clock (T-TSC) is part of "network"
- Case 1 applicable for Wireless RU:
  - *Endpoint* implies flexibility in choice of clock bandwidth
    - No chain reaction to worry about
    - Reduce bandwidth to reject noise from FH network
    - **Local oscillator performance determines allowed bandwidth reduction**
  - Using PHY layer recovered clock (eSyncE) to support PTP layer is "optional"
    - **Long-term frequency accuracy maintained with narrow bandwidth, limited by oscillator performance**

Wireless RU Timing

6.3.3.4 Config LLS-C2 (Option A: O-DU is the nearest common T-BC)

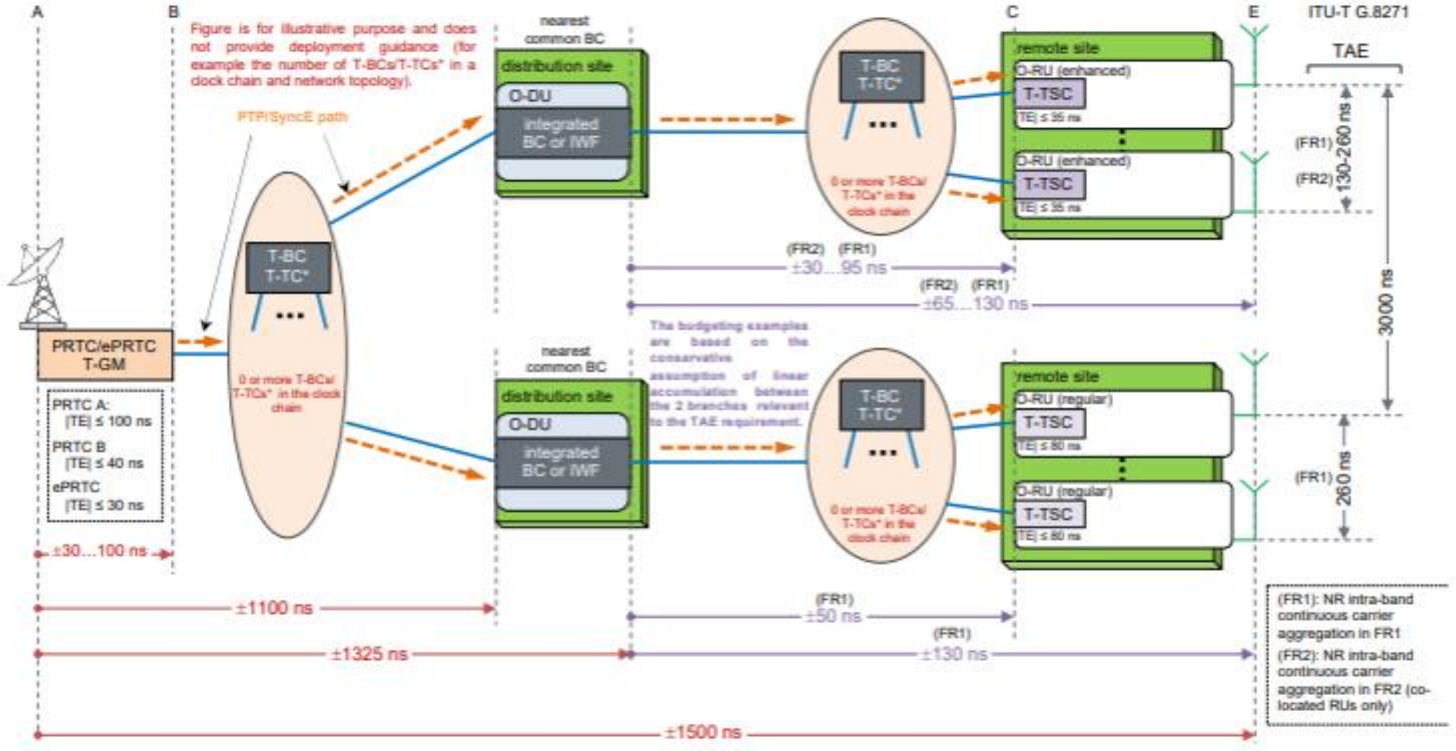
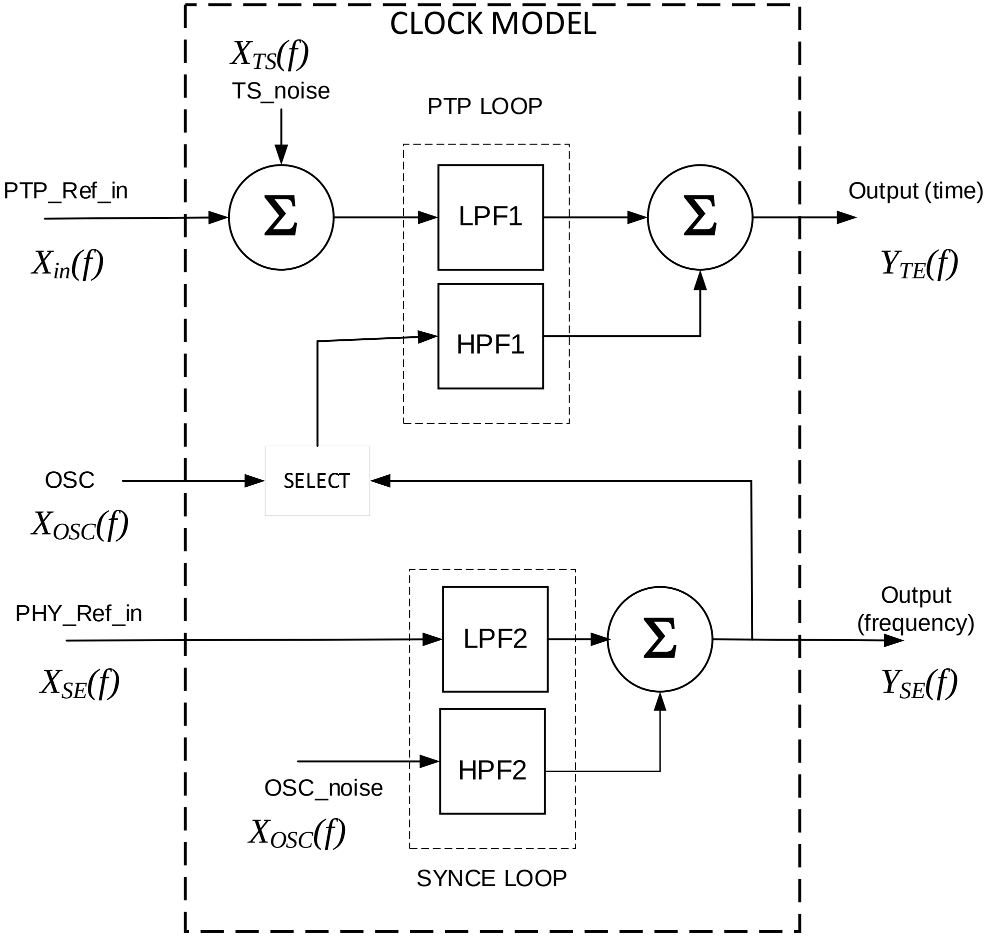


Figure 6.3.3-4: O-DU is the nearest common T-BC

Extracted from O-RAN.WG9.XTRP-SYN.0-R003-v05.00.pdf

- Timing performance dictated by End Application
  - Time Alignment Error (TAE) better than 3000ns between any two antennas.
  - Time Alignment Error (TAE) better than 130ns between antennas in the same cluster. TAE better than 65ns between RU and *TimeTransmitter* for the cluster (typically the DU).
  - Front Haul network is normally assumed to be Full Timing Support
- Assumptions for this analysis:
  - Front Haul is a chain of 4 T-BCs between DU and RU

Endpoint Clock Time Error Variance Estimation



"SELECT": chose driver for PTP loop (OSC or PHY_Layer)

LPFx and HPFx are not independent and have the same cut-off frequency.

- PTP Loop driven by OSC:

$$Y_{TE}(f) = \left(|H_{L1}(f)|\right)^2 \cdot \left(X_{in}(f) + X_{TS}(f)\right) + \left(|H_{H1}(f)|\right)^2 \cdot X_{OSC}(f)$$

- PTP Loop driven by PHY_Layer Clock ("Hybrid Mode"):

$$Y_{TE}(f) = \left(|H_{L1}(f)|\right)^2 \cdot \left(X_{in}(f) + X_{TS}(f)\right) + \left(|H_{H1}(f)|\right)^2 \cdot Y_{SE}(f)$$

- PHY_Layer Clock Error Spectrum:

$$Y_{SE}(f) = \left(|H_{L2}(f)|\right)^2 \cdot X_{SE}(f) + \left(|H_{H2}(f)|\right)^2 \cdot X_{OSC}(f)$$

- Endpoint Clock Time Error Variance:

$$\sigma_{TE}^2 = \int_0^{f_S} Y_{TE}(f)\,df$$

- Rule of Thumb: $\max|TE| \approx 4 \cdot \sigma_{TE}$

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Example Calculations and Analysis

- Basic Parameters:
  - Target Max|TE_L| (between DU and RU) = 65ns $\Rightarrow \sigma_{TE}^2 < \left(\frac{65}{4}\right)^2 = 264\ (ns)^2$
  - Front Haul network = 4 devices adhering to Enhanced Synchronous Ethernet
    - All 4 with Class C noise generation (2 ns TDEV)
    - Mix of Class C (2 ns TDEV) and Class A/B (4 ns TDEV)
  - Oscillator: OCXO with ADEV = $1\text{x}10^{-10}$ (TDEV = 0.057735 ns) at tau=1 sec
  - Packet rate = 16/sec corresponding to f_S = 16 Hz
- Time error variance computed for the following:
  - PHY layer loop BW = 1 Hz (enhanced Synchronous Ethernet)
  - Four choices of PTP layer loop BW: 0.1, 0.01, 0.003, 0.001 Hz
  - PTP layer clock driven by either the PHY layer clock (derived from Ethernet) or driven directly by the OSC

Example Calculations (all 4 Class C T-BCs in Front Haul)

PTP Layer BW →	0.1 Hz		0.01 Hz		0.001 Hz	
	PHY Layer contrib. (ns)^2	Max|TE_L| (ns)	PHY Layer contrib. (ns)^2	Max|TE_L| (ns)	PHY Layer contrib. (ns)^2	Max|TE_L| (ns)
PTP Loop Driven by **OSC** directly →	0.02	45	3.4	37	**353**	**78**
PTP Loop Driven by **PHY** Layer (**noise** at eSyncE TDEV limit) →	14	47	87	52	**326**	**75**
PTP Loop Driven by **PHY** Layer (**Sinusoid** at eSyncE MTIE limit) →	281 (@ 0.1Hz)	**69**	2490 (@0.045Hz)	**87**	2500 (@0.045Hz)	**71**
PTP layer noise input (**Front Haul**) contribution to Time Error variance →	127 (ns)^2		84 (ns)^2		29 (ns)^2	

Note: Bold red font implies error greater than 65ns ($\sigma^2 > 264$)

Example Calculations (Mix of Class C and Class A/B T-BCs)

PTP loop driven by oscillator directly

PTP BW →	0.1 Hz		0.01 Hz		0.003 Hz		0.001 Hz	
	PTP layer contrib. $(ns)^2$	Max|TE_L| (ns)	PTP layer contrib. $(ns)^2$	Max|TE_L| (ns)	PTP layer contrib. $(ns)^2$	Max|TE_L| (ns)	PTP layer contrib. $(ns)^2$	Max|TE_L| (ns)
4 Class C, 0 A/B →	127	45	84	37	55	**39**	29	**78**
3 Class C, 1 A/B →	219	59	147	49	97	**47**	51	**80**
2 Class C, 2 A/B →	313	**71**	210	58	138	**53**	72	**82**
1 Class C, 3 A/B →	409	**81**	273	**66**	180	**59**	94	**85**
0 Class C, 4 A/B →	506	**90**	336	**74**	221	**64**	116	**87**
PHY layer noise (**OSC drives PTP loop**) contribution →	0.02 $(ns)^2$		3.4 $(ns)^2$		39 $(ns)^2$		**353** $(ns)^2$	

Note: Bold red font implies error greater than 65ns ($\sigma^2 > 264$)

Analysis and Comments

- From a noise perspective, for very tight requirements such as in a wireless RU, the endpoint clock with an adequate oscillator can operate without SyncE.
  - As a design choice allocate noise allowance between PTP and OSC contributions
  - Establish PTP bandwidth that supports this allocation to PTP layer
  - Verify that this bandwidth supports OSC contribution with chosen oscillator
  - Repeat as necessary….this mandates that the method is simple and rapid
- The known advantage of SyncE/eSyncE is the availability of a good frequency reference. However, standards compliant eSyncE can introduce significant clock noise.
  - When the PHY layer (SyncE/eSyncE) clock is utilized by the PTP layer in hybrid mode, the performance of the oscillator is not a major factor if PHY layer BW is 1Hz or greater.
  - The only shortcoming is based on allowable wander on the (enhanced) Synchronous Ethernet network interface. Reducing this requires an effective PHY layer BW of (much) less than 1Hz.

Concluding Remarks

- The use of traditional filter analyses provides quick results, albeit approximate.
  - Note: many clock recovery servo loop algorithms use non-linear methods such as packet selection and the time error performance should be better than that estimated by linear-time-invariant methods.
  - The underlying assumptions made here are reasonable to get an approximate estimate of time error behavior.
  - The quick results allow for an iterative approach to the design.
- The oscillator plays a crucial role in Endpoint Clocks for permitting narrow bandwidths.
- Oscillator manufacturers generally provide only the ADEV at 1 second. It can be shown that using this for the knee (for A_K and τ_K) is quite appropriate in most, if not all, cases (see information in back-up).

Thank You

Any questions?

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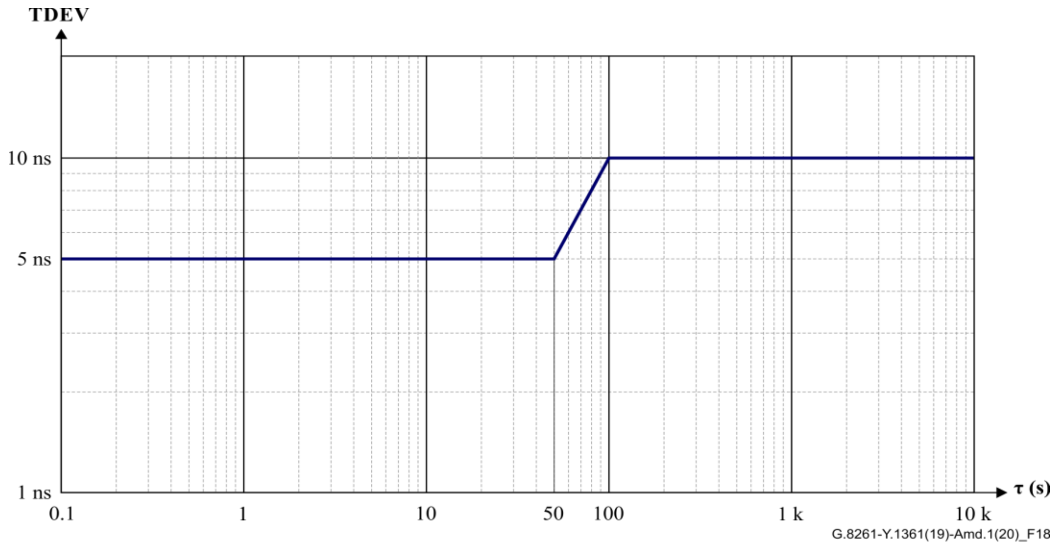
Back-Up Slides

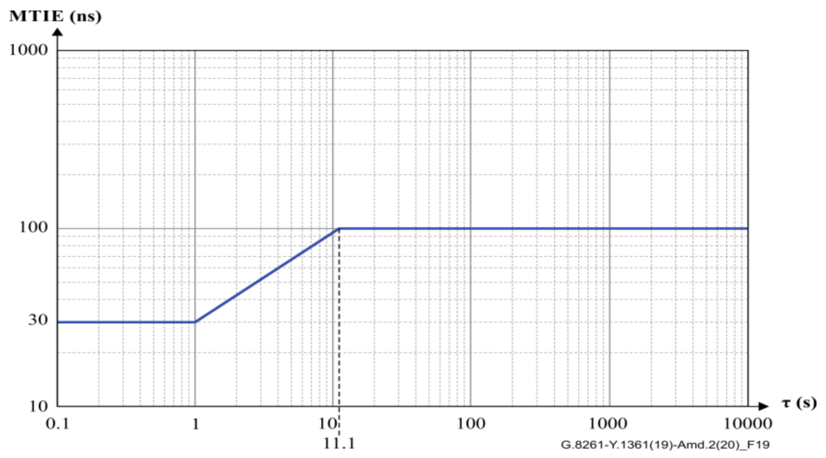
Enhanced Synchronous Ethernet Interface Noise Properties



G.8261: Figure 18 – Network limit for wander (TDEV) at enhanced synchronous equipment clock interfaces

G.8261: Table 9 – Network limit for wander at enhanced synchronous equipment clock interfaces expressed in TDEV

Observation interval τ (s)	TDEV requirement (ns)
$0.1 < \tau \leq 50$	5
$50 < \tau \leq 100$	$0.1\ \tau$
$100 < \tau \leq 10\,000$	10



G.8261: Figure 19 – Network limit for wander (MTIE) at enhanced synchronous equipment clock interfaces in a short chain of up to 4 clocks, traceable to a PRTC-B

G.8261: Table 10 – Network limit for wander at enhanced synchronous equipment clock interfaces expressed in MTIE

Observation interval τ (s)	MTIE requirement (ns)
$0.1 < \tau \leq 1$	30
$1 < \tau \leq 11.1$	$30\ \tau^{0.5}$
$11.1 < \tau \leq 10\,000$	100

Enhanced Synchronous Ethernet Interface Noise Properties

G.8261: Table 10 – Network limit for wander at enhanced synchronous equipment clock interfaces expressed in MTIE

Observation interval τ (s)	MTIE requirement (ns)
0.1 < τ ≤ 1	30
1 < τ ≤ 11.1	$30\ \tau^{0.5}$
11.1 < τ ≤ 10 000	100

G.8261: Table 9 – Network limit for wander at enhanced synchronous equipment clock interfaces expressed in TDEV

Observation interval τ (s)	TDEV requirement (ns)
0.1 < τ ≤ 50	5
50 < τ ≤ 100	0.1 τ
100 < τ ≤ 10 000	10

Permissible amplitude for sinusoidal wander:

$$x(t) = A \cdot \sin(2\pi f_0 t) \Rightarrow MTIE_x(\tau) = 2A \ \ for\ \tau \geq \left(\frac{1}{2f_0}\right)$$

For 5 Hz > f_0 > 0.5 Hz : $A \leq 15\ ns$

For 0.5 Hz > f_0 > 0.045 Hz : $A \leq \frac{15}{\sqrt{2f_0}}\ ns$

For 0.045 Hz > f_0 > 0.05 mHz : $A \leq 50\ ns$

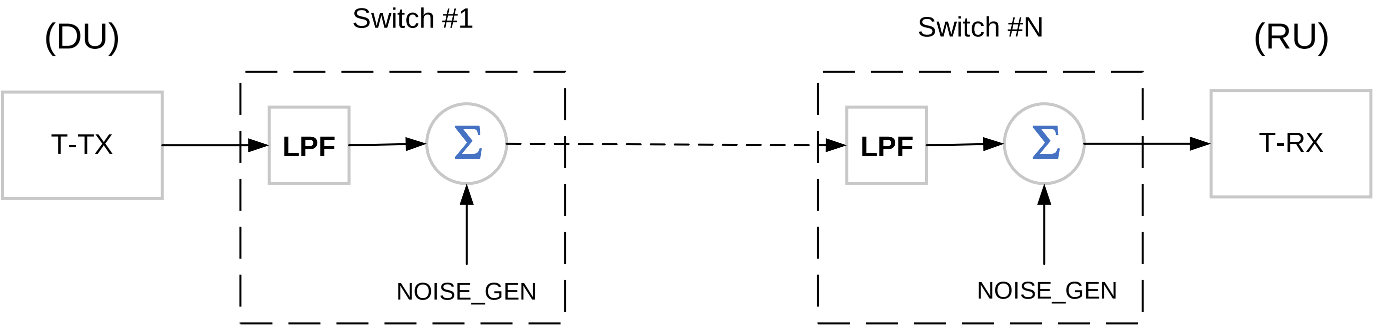
Power spectrum for random process wander:

For $f > f_1$ (= 0.3/50 Hz): $S_\eta(f) = \left(\frac{0.75}{f}\right) \cdot (5)^2$

For $f_1 > f > f_2$: $S_\eta(f) = \left(\frac{0.75}{f}\right) \cdot (0.1)^2 \cdot \left(\frac{0.3}{f}\right)^2$

For $f < f_2$ (= 0.3/100 Hz) : $S_\eta(f) = \left(\frac{0.75}{f}\right) \cdot (10)^2$

Analytical Model for Network Noise Accumulation



Noise Generation spectrum : $S_\eta(f)$

Low Pass Filter : $H_L(f)$

Noise generation TDEV : $\sigma_\eta(\tau)$

Table 7-5 – Dynamic time error low-pass filtered noise generation (TDEV) for T-BC/T-TSC with constant temperature (within ±1K)

T-BC/T-TSC Class	TDEV limit [ns]	Observation interval τ [s]
A	4	$m < \tau \le 1\,000$ (Note)
B	4	$m < \tau \le 1\,000$ (Note)
C	2	$m \le \tau \le 1\,000$ (Note)
D	For further study	For further study
NOTE – The minimum τ value *m* is determined by packet rate of 16 packet per second ($m = 1/16$) or 1 PPS signal ($m = 1$).		

Extracted from G.8273.2

- Output noise spectrum as function of input (for each switch):

$$X_n(f) = |H_L(f)|^2 \cdot X_{(n-1)}(f) + S_\eta(f)$$

- Low Pass Filter (LPF) characteristic (2nd order) assuming maximally-flat equivalent:

$$|H_L(f)|^2 = \frac{1}{1+\left(\frac{f}{f_C}\right)^4}$$

- Spectrum from TDEV (approximation):

$$S_\eta(f) = \left(\frac{0.75}{f}\right) \cdot \left(\sigma_\eta\left(\tau = \frac{0.3}{f}\right)\right)^2 \quad (ns)^2/Hz$$

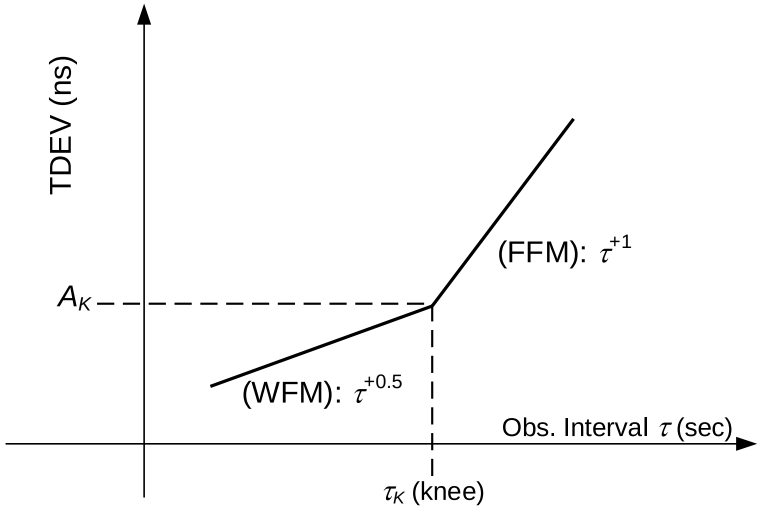
- For Class C T-BC (for $0.001 < f < 16$):

$$S_\eta(f) = \left(\frac{0.75}{f}\right) \cdot (2)^2 \quad (ns)^2/Hz$$

- For Class A/B T-BC (for $0.001 < f < 16$):

$$S_\eta(f) = \left(\frac{0.75}{f}\right) \cdot (4)^2 \quad (ns)^2/Hz$$

Two-parameter Model for the Oscillator



$$TDEV(\tau) = \begin{cases} A_K \cdot \sqrt{\left(\frac{\tau}{\tau_K}\right)} & ; \ \tau < \tau_K \\ A_K \cdot \left(\frac{\tau}{\tau_K}\right) & ; \ \tau \geq \tau_K \end{cases}$$

Note: For large τ:

$$ADEV(\tau) \cong MDEV(\tau) = \frac{\sqrt{3}}{\tau} \cdot TDEV(\tau)$$

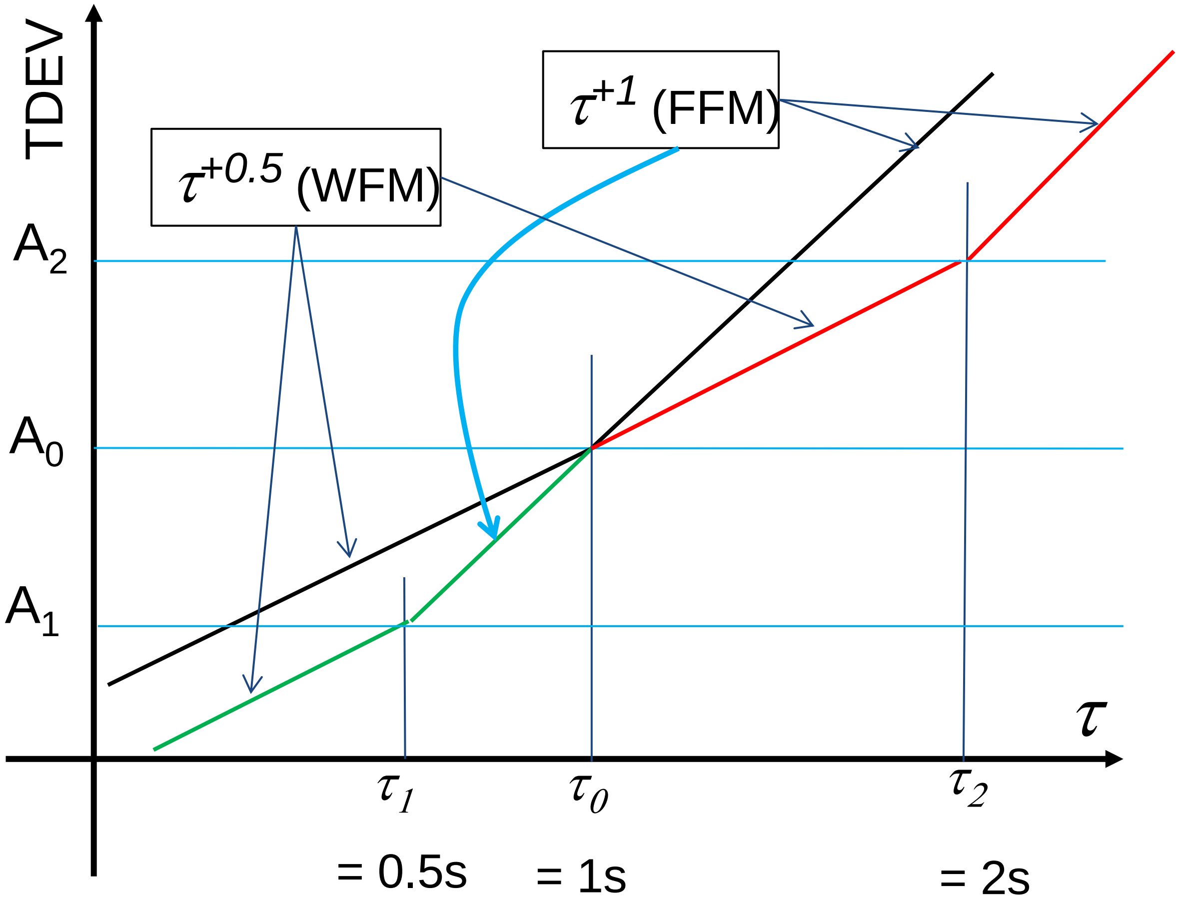
Assumptions:

- Temperature is essentially constant
- In locked mode frequency offset and aging can be ignored
- The random noise exhibits white FM (WFM) type for shorter observation intervals and flicker FM (FFM) for longer intervals
- The high-pass characteristic seen by the oscillator is of order 2 or greater so there are no numerical anomalies for $f \sim 0$
- Behavior described by 2 parameters (A_K and τ_K)

$$X_{OSC}(f) = \left(\frac{0.75}{f}\right) \cdot \left(\sigma_{OSC}\left(\tau = \frac{0.3}{f}\right)\right)^2$$

$$X_{OSC}(f) = \begin{cases} {A_K}^2 \cdot \left(\frac{0.75}{f}\right) \cdot \left(\frac{0.3}{f \cdot \tau_K}\right) & ; \ f > \frac{0.3}{\tau_K} \\ {A_K}^2 \cdot \left(\frac{0.75}{f}\right) \cdot \left(\frac{0.3}{f \cdot \tau_K}\right)^2 & ; \ f \leq \frac{0.3}{\tau_K} \end{cases}$$

Utilizing Oscillator specification of ADEV @ tau=1s



A_0	A_1	A_2
0.057735ns	0.0288375ns	0.08165ns

Oscillator spec: ADEV = $1\text{x}10^{-10}$ @ $\tau = 1\text{s}$

Approach:

- Assume that the break point is at $\tau = 1\text{s}$.
- For such oscillators and the bandwidths of interest, the estimate of noise leaking into the time output will be conservative.
- In the following, three cases are evaluated, all three have ADEV = $1\text{x}10^{-10}$ @ $\tau = 1\text{s}$.
- Time error contribution (in $(\text{ns})^2$) with 0.1Hz measurement filter evaluated below.

PTP Layer Bandwidth

τ_k	A_k	0.1Hz	0.01Hz	0.001Hz
1s	0.058ns	0.0177	3.43	353.2
0.5s	0.029ns	0.0176	3.42	352.5
2.0s	0.082ns	0.0091	1.72	176.6

Example Calculations (4 switches – Either Class C or Class A/B T-BCs)

		PTP BW = 0.1Hz		PTP BW = 0.01Hz		PTP BW = 0.003Hz		PTP BW = 0.001Hz	
SyncE	FH Ntwk	Pwr(TE_L) $(ns)^2$	Max|TE_L| (ns) (4σ)	Pwr(TE_L) $(ns)^2$	Max|TE_L| (ns) (4σ)	Pwr(TE_L) $(ns)^2$	Max|TE_L| (ns) (4σ)	Pwr(TE_L) $(ns)^2$	Max|TE_L| (ns) (4σ)
PHY BW = 1.0 Hz	4 Class C	141	47	171	52	226	60	**355**	**75**
	4 Class A/B	**520**	**91**	**423**	**82**	**392**	**79**	**442**	**84**
PHY BW = 0.1 Hz	4 Class C	132	46	157	50	212	58	**341**	**74**
	4 Class A/B	**511**	**90**	**408**	**81**	**378**	**78**	**427**	**83**
PHY BW = 0.01 Hz	4 Class C	127	45	96	39	143	48	**272**	**66**
	4 Class A/B	**506**	**90**	**348**	**75**	**309**	**70**	**359**	**76**
OSC ONLY	4 Class C	127	45	87	37	94	30	**382**	**78**
	4 Class A/B	**506**	**90**	**339**	**74**	260	64	**469**	**87**

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Example Calculations (4 switches - Mix of Class C and Class A/B T-BCs)

		PTP BW = 0.1Hz		PTP BW = 0.01Hz		PTP BW = 0.003Hz		PTP BW = 0.001Hz	
SyncE	FH Ntwk	Pwr(TE_L) (ns)^2	Max|TE_L| (ns) (4σ)	Pwr(TE_L) (ns)^2	Max|TE_L| (ns) (4σ)	Pwr(TE_L) (ns)^2	Max|TE_L| (ns) (4σ)	Pwr(TE_L) (ns)^2	Max|TE_L| (ns) (4σ)
PHY BW = 1.0 Hz	3 Class C	233	61	234	61	**268**	65	**377**	**78**
	3 Class A/B	**423**	**82**	**360**	**76**	**351**	**75**	**442**	**84**
PHY BW = 0.1 Hz	3 Class C	224	60	220	59	254	64	**363**	**76**
	3 Class A/B	**413**	**81**	**346**	**74**	**337**	**73**	**428**	**83**
PHY BW = 0.01 Hz	3 Class C	219	59	159	50	185	54	**294**	**69**
	3 Class A/B	**409**	**81**	**285**	68	268	65	**359**	**76**
OSC ONLY	3 Class C	219	59	150	49	136	47	**404**	**80**
	3 Class A/B	**409**	**81**	276	66	219	59	**469**	**87**

Thank You

Any questions?

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