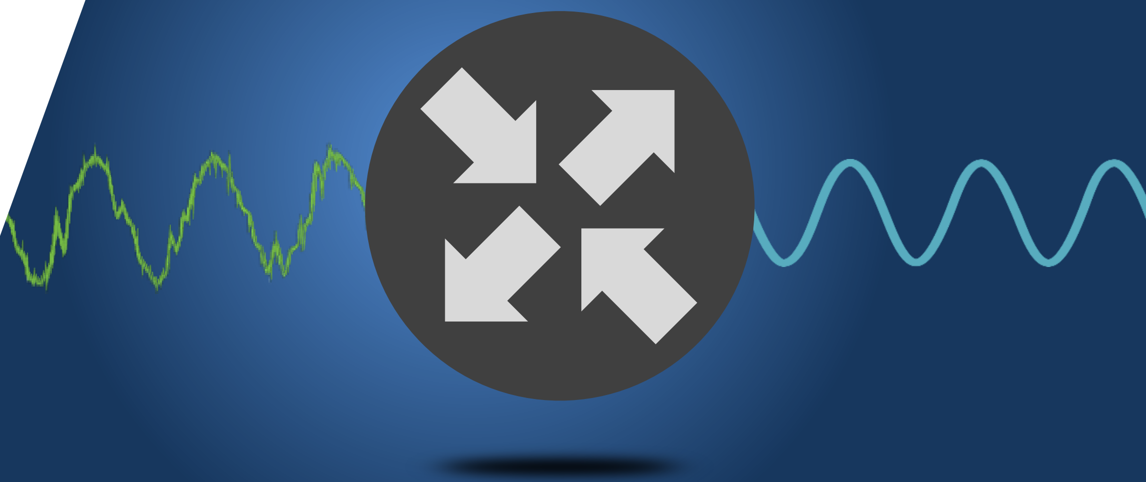
TECHNICAL OVERVIEW

The accuracy of Telecom Boundary Clocks (T-BCs) is essential to the successful roll-out of 5G, in addition to supporting LTE-A and TDD-LTE. The ITU-T has updated specifications for T-BCs in Recommendation G.8273.2 to cover this range of applications. This Technical Overview describes what a boundary clock is, and explains the critical performance parameters defined in G.8273.2.

Testing a T-BC to

ITU-T G.8273.2



Contents

1. Boundary Clocks for Full Timing Support

A PTP boundary clock recovers the timing from an upstream PTP node, and forwards it to any downstream nodes to which it is connected. It may filter the timing to reduce noise, although it isn't required to do so by the IEEE1588 definition. It also participates in the Best Master Clock Algorithm, the algorithm that determines the synchronization topology of a network.

The ITU-T has defined a performance specification for the telecom boundary clock (T-BC) to be used in the G.8275.1 profile for full timing support. The profile requires the use of a boundary clock at every network element through which the PTP flow passes. This helps to minimise the build-up of time error through the network. The boundary clock specification is defined in Recommendation G.8273.2. It follows the same approach as the other ITU-T clock specifications, with the five key elements of a clock specification:

- noise generation
- noise transfer
- noise tolerance
- transient response
- holdover (or long-term transient response)

In terms of a PTP time clock, the term "noise" means "time error". It is characterised using three parameters:

- Maximum absolute time error (max|TE|) – the maximum difference from the reference clock, either positive or negative. This is measured on the unfiltered data.
- Constant time error (cTE) – a fixed offset from the reference clock, e.g. such as might be produced by delay asymmetry within the device.
- Dynamic time error (dTE) – the variation of time error with respect to the reference. This is further sub-divided into two parts:
    - Low-pass filtered dTE, using a 0.1Hz low-pass filter to remove quantization noise and other short-term components. This is analogous to "wander" in conventional clocks, and represents the amount of noise that will propagate down the chain. Higher-frequency noise is removed by the filtering action of the boundary clock.
    - High-pass filtered dTE, using a 0.1Hz high-pass filter to remove the low-frequency wander components. This is analogous to "jitter" in conventional clocks, and although this noise is not propagated down the chain, it is present at the input to the next clock, therefore it must be controlled to prevent overloading the input with too much high-frequency noise.

These terms are defined in ITU-T Recommendation G.8260, and described in more detail in the Calnex white paper "Time and Time Error: A Guide to Network Synchronization, CX5013".

PTP clocks communicate time using messages, in both directions, in order to estimate the delay through the network. Each message will have a timestamp associated with it, and each of these individual timestamps will have an error component. The time of the clock may be calculated from a pair of messages travelling in each direction (e.g. the ***sync*** and ***delay_request*** messages), and the time error of the clock will be the mean of the time errors of the individual timestamps in that pair. This is known as the ***two-way time error***.

In all cases below, when time error is discussed, it is this two-way time error that is considered, not the errors in the individual timestamps.

1.1 Functional Model

A PTP boundary clock has at least two ports. The first is a PTP slave port, receiving timing from an upstream clock. The boundary clock is synchronised to this source of time. The other port(s) are PTP master ports, supplying time to downstream clocks. In the G.8273.2 specification, a T-BC may also make use of a stable frequency source such as Synchronous Ethernet to help stabilise the clock.

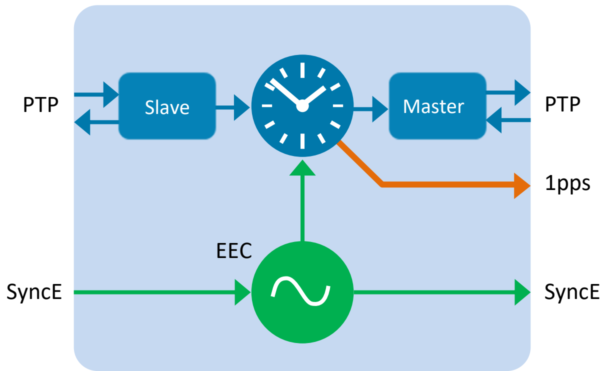


Figure 1: Telecom Boundary Clock (T-BC)

2. T-BC Specification

As mentioned earlier, G.8273.2 follows the same approach as the other ITU-T clock specifications, with the five key elements of noise generation, noise transfer, noise tolerance, transient response and holdover, where noise in the context of time clock means time error. The following sections describe each of the five elements of the clock specification.

2.1 Time Error Generation

This is a measure of the intrinsic amount of “noise” (or time error) introduced by the T-BC. It is defined as the time error at the output of the device with an ideal signal on the input, as shown in Figure 2. The specification applies to both the 1pps and the PTP outputs of the T-BC.

G.8273.2 specifies four classes of performance for time error generation: Class A, for use in shorter chains of T-BCs (up to 10 clocks), Class B, which is expected to be used in longer chains of up to 20 clocks, and Classes C and D which have been added for 5G enhanced time applications. Class C is intended for 10 clock chains, and Class D for chains up to 20 clocks as well as fronthaul applications.

G.8273.2 defines limits on time error generation in terms of all three parameters, maximum absolute time error (max|TE|), constant time error (cTE) and dynamic time error (dTE). The dTE is further divided into low-pass filtered and high-pass filtered measurements, similar to how phase noise was divided into wander and jitter in the frequency clock specifications. For the highest performance Class D devices, a 0.1 Hz low-pass filtered (max|TEL|) metric is used for the very tight performance specification.

The low-pass filtered dTE represents the effect on the overall time error of the synchronisation chain. This is because subsequent clocks will contain a similar low-pass filter, so it is only the low-frequency components of time error that will propagate down the chain. It is measured in terms of the metrics MTIE and TDEV, similar to phase wander.

The constraint on high-pass filtered dTE limits the amount of high-frequency noise permitted at the output of the boundary clock. While this noise is filtered out by the next boundary clock in the chain, this limit prevents the next boundary clock from being overwhelmed by high-frequency noise on its input. Table 1 shows the various time error generation parameters for a T-BC:

Parameter	Class A	Class B	Class C	Class D	Notes
Max|TE|	100ns	70ns	30ns	-	Unfiltered measurement, absolute value
Max|TE$_L$|	-	-	-	5ns	0.1Hz low-pass filter, 1000s measurement, absolute value
cTE	±50ns	±20ns	10ns	-	Averaged over 1000s
dTE (0.1Hz low pass filtered) MTIE	40ns	40ns	10ns	-	1000s observation interval (constant temp)
	40ns	40ns	-	-	10000s observation interval (variable temp)
dTE (0.1Hz low pass filtered) TDEV	4ns	4ns	2ns	-	1000s observation interval (constant temp)
dTE (0.1Hz high pass filtered)	70ns	70ns	-	-	Peak-to-peak value, measured over 1000s

Table 1: T-BC Time Error Generation Limits

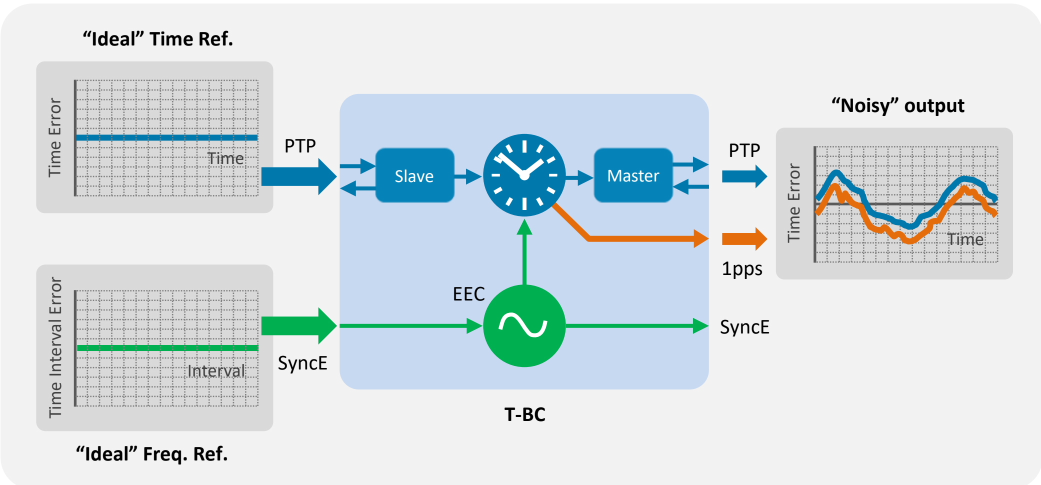


Figure 2: T-BC Time Error Generation

2.2 Time Error Tolerance

Time error tolerance is the maximum amount of time error a clock is required to tolerate on its inputs. A T-BC has both SyncE and PTP inputs, and may expect both of these to be “noisy” in a real deployment. Therefore time error tolerance is defined with “noise” on both inputs simultaneously, as shown in Figure 3. Noise in the context of the PTP input is the two-way time error, while for the SyncE input it is the phase wander.

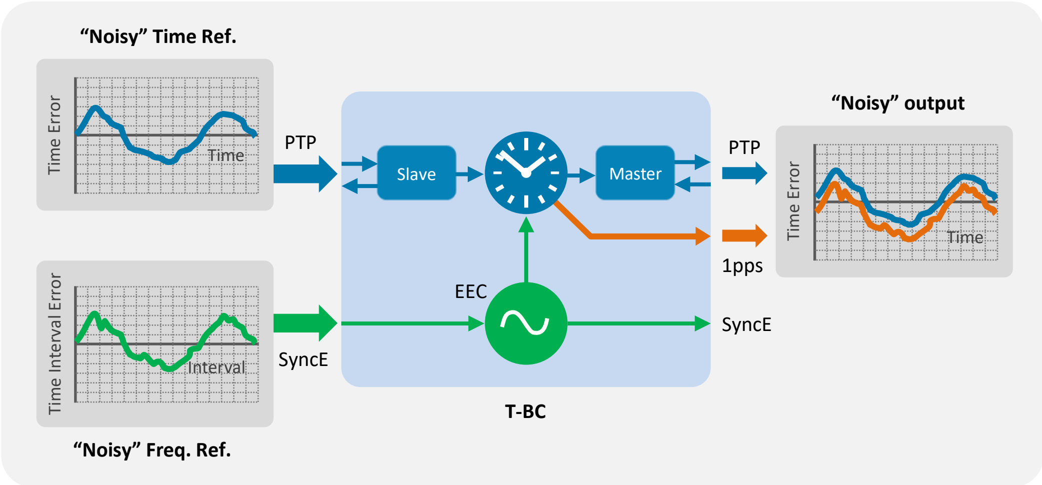


Figure 3: T-BC Time Error Tolerance

The output time error is not specified for a time error tolerance test. This is standard practice for a clock that is part of a chain. The output time error is characterised by the time error generation test, and it is not necessary to prove this again. Therefore the objective of the time error tolerance test is to prove that the clock works normally without attempting to switch references or generate alarm messages.

The maximum amount of noise that should be tolerated on the PTP input is defined by the dTE mask for the network limit, defined in G.8271.1. This is shown in Figure 4.

The maximum amount of noise that should be tolerated on the SyncE input is defined in G.8262 (clause 9). The method to test it is also discussed in G.8262.

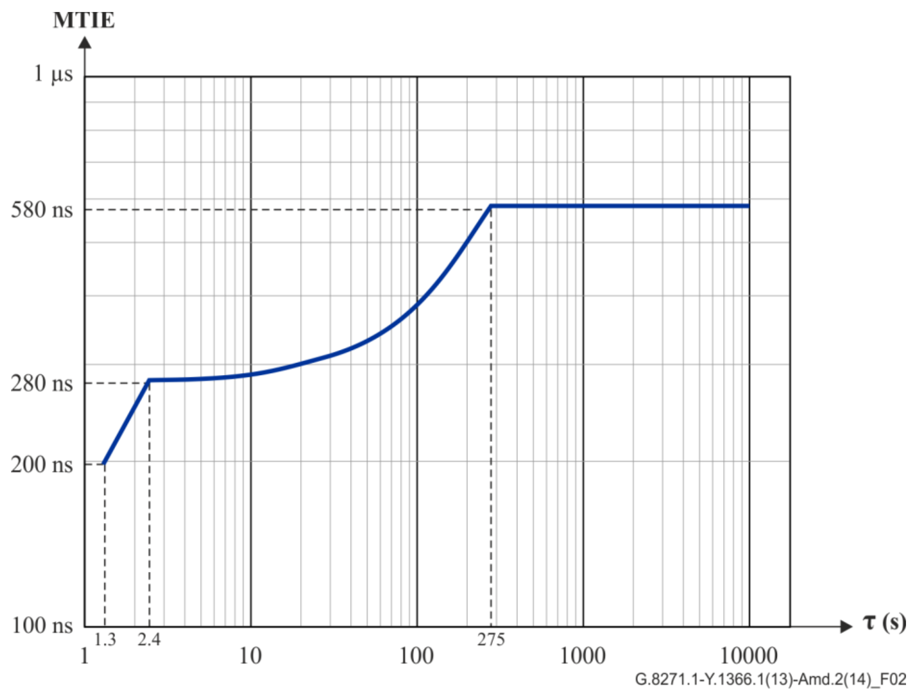


Figure 4: MTIE mask for dTE network limit (Figure 7-2 from G.8273.2)

2.3 Time Error Transfer

Time error transfer is a measure of how much "noise" (time error) present at the input is transferred to the output of the clock. The clock should act as a filter, removing some of the noise present at the input, therefore it is usually expressed in terms of a filter bandwidth.

There are two filter characteristics to measure. The first is the time error transfer from PTP to PTP (and also PTP to 1pps), i.e. the boundary clock itself. PTP interfaces are generally quite noisy at frequencies close to the message rate. This is because of quantization noise in the timestamps, and also positional quantization in the physical layer components as the packets cross from the line clock domain to the internal clock domain. Therefore, G.8273.2 defines a low-pass filter function from PTP input to PTP output to remove the interface noise and prevent it from propagating down a chain of T-BCs. The bandwidth of this filter is between 0.05 and 0.1Hz, as shown in Figure 5.

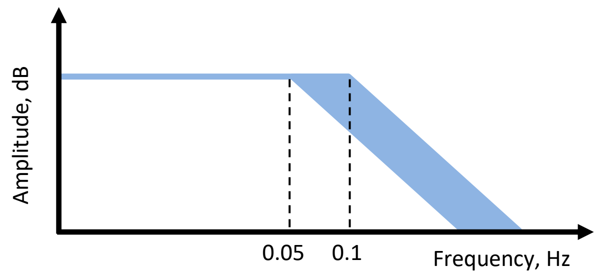


Figure 5: PTP to PTP Transfer Function

The transfer function from the SyncE input to PTP output is more complex. Firstly, there is a low-pass function in the EEC itself, defined in G.8262 to have a bandwidth of between 1 and 10Hz. The boundary clock then acts as a high-pass filter to the SyncE signal, at the same bandwidth as the PTP to PTP low pass filter. This high-pass function is a natural consequence of the way the clock works: it smooths out high frequency noise by following the local frequency reference (in this case, the SyncE), while following the PTP input at low frequencies.

The net result is that any noise (or phase wander) on the SyncE input is band-pass filtered, as shown in Figure 6.

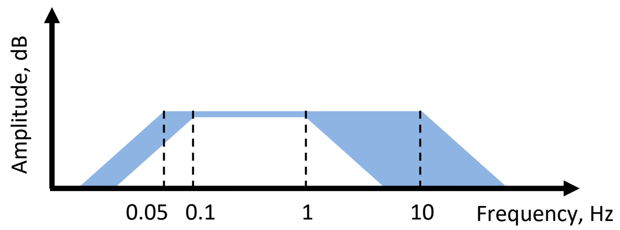


Figure 6: SyncE to PTP Transfer Function

The purpose of the time error transfer test is to measure the frequency response of the T-BC, and verify that the filtering conforms to the limits described in G.8273.2.

2.3.1 Measuring the PTP to PTP Transfer Function

The transfer function can be measured by applying sinusoidal time error at different frequencies to the PTP input, while keeping the SyncE input at a constant frequency, as shown in Figure 7. The filter characteristic can be seen by observing the attenuation of those tones at the output.

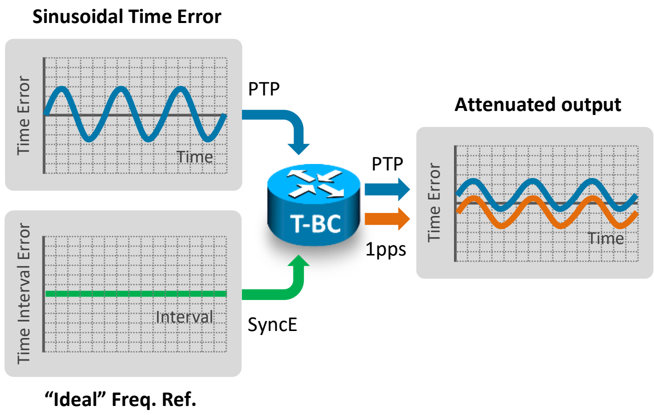


Figure 7: Measuring PTP to PTP Time Error Transfer

In principle, this is a simple process: apply a set of tones at the input and measure the amplitude produced at the output. However, the PTP message rate of 16Hz is very low compared to the tone frequencies required to determine the bandwidth of the filter. This may cause unwanted interactions between the message rate and the tone frequencies that can lead to unexpected results.

Secondly, the short-term noise on the PTP output can be high enough to obscure the frequency response of the filter, and this must be removed to determine the real output amplitude.

Appendix VI of G.8273.2 explores these issues and recommends a set of tone frequencies to be used, and methods to remove the output noise of the device under test. This is explained in more detail in a companion application note, "Measuring Time Error Transfer of G.8273.2 Telecom Boundary Clocks".

2.3.2 Measuring the SyncE to PTP Transfer Function

For the SyncE to PTP transfer function, a similar method can be used – applying sinusoidal wander to the SyncE input with an "ideal" time reference at the PTP input, as shown in Figure 8:

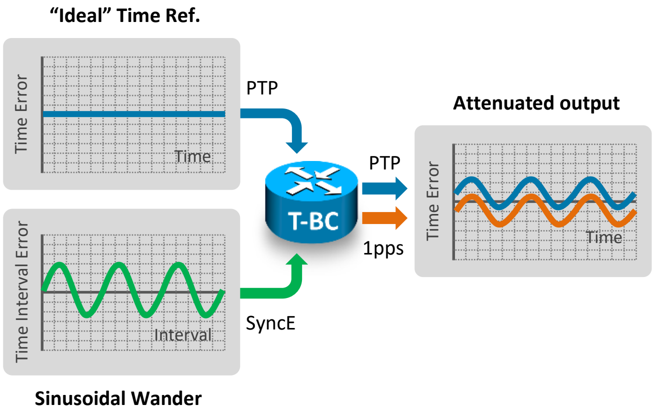


Figure 8: Measuring SyncE to PTP Time Error Transfer

The interaction with the PTP message rates and the output noise of the packet interface are still issues for accurate measurement. As for PTP to PTP time error transfer, this is described in more detail in Appendix VI, and in the Calnex application note, "Measuring Time Error Transfer of G.8273.2 T-BCs".

2.4 Short-term Transient Response

Short-term transient response refers to the time error generated when a clock switches over from one input reference to another e.g. in the event of a reference failure. G.8273.2 only defines the short-term transient response to a rearrangement in the physical layer frequency (SyncE) reference. It does not define the transient response for a rearrangement in the PTP layer at present.

A reference switch in the physical layer frequency reference at the previous node to the T-BC can generate a large transient in the frequency reference input to the T-BC. This in turn will produce significant time error in the PTP output of the T-BC if is allowed to propagate through the clock. Therefore a T-BC must reject this transient on its input.

It can achieve this by monitoring the ESMC messages on the SyncE interface. These report the QL (Quality Level) of the SyncE signal, and indicate when the signal is temporarily not traceable to a primary reference clock. On receipt of a degraded QL, the T-BC must either stop using the SyncE signal, and rely instead on its own local oscillator, or turn off the low-pass filter, allowing the PTP to correct the time error more quickly. When traceability of the SyncE signal is restored, the T-BC can go back to using the SyncE signal.

Annex B of G.8273.2 Amd. 2 defines the following mask for the clock output in the event of a transient on the SyncE input. The mask is a composite of the expected response of the clock using either one of the two methods mentioned, rejecting the SyncE signal, or temporarily disabling the low-pass filter.

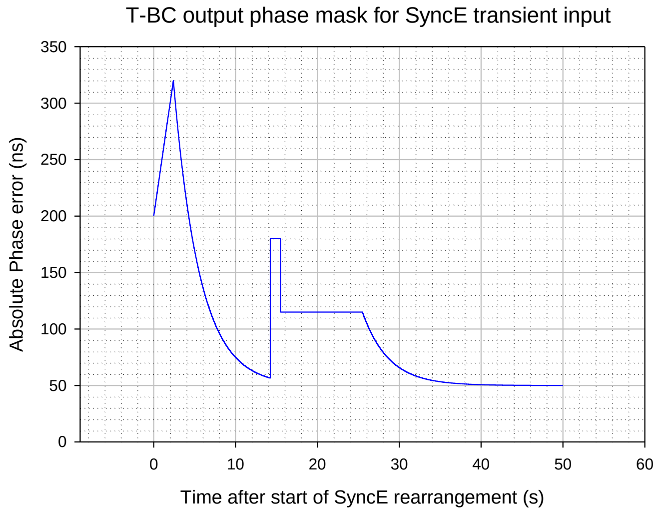


Figure 9: Phase error mask during a SyncE transient (Figure B.1 from G.8273.2 Annex B)

The method to verify compliance with the mask shown in Figure 9 is described in G.8273 Appendix III. The phase transient to be applied to the input SyncE signal is shown in Figure 10. During the transient, the input QL-value in the ESMC messages is changed from QL-PRC to QL-EEC in the first shaded area (from 1.8 to 2.0s), and back to QL-PRC in the second shaded area (from 15.18 to 15.5s).

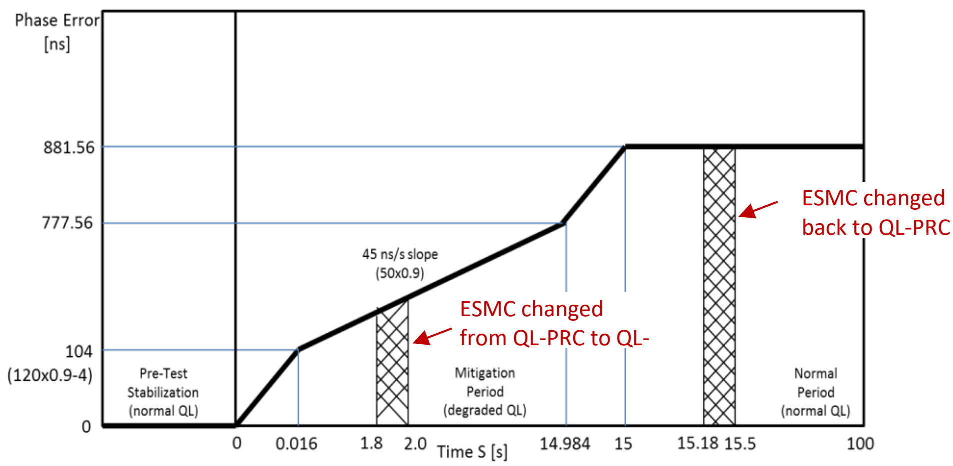


Figure 10: SyncE Transient Input Pattern (Fig. III.2 from G.8273 Appendix III)

2.5 Long-term Transient Response (Holdover)

The long-term transient response (sometimes known as holdover) defines the performance of the clock in the event of a loss of the input references, when there is no viable alternate reference to switch to. For a T-BC, this may be assisted holdover, using the SyncE signal to maintain the timebase of the clock advancing at a stable rate.

G.8273.2 defines the holdover performance in SyncE-assisted mode using the MTIE mask shown in Figure 11 (plotted from the values given in Table 7-6 of G.8273.2). This is derived from the EEC noise generation specification in G.8262, plus a small allowance for a transient caused by entering holdover. The holdover performance when not using SyncE assistance is not currently defined.

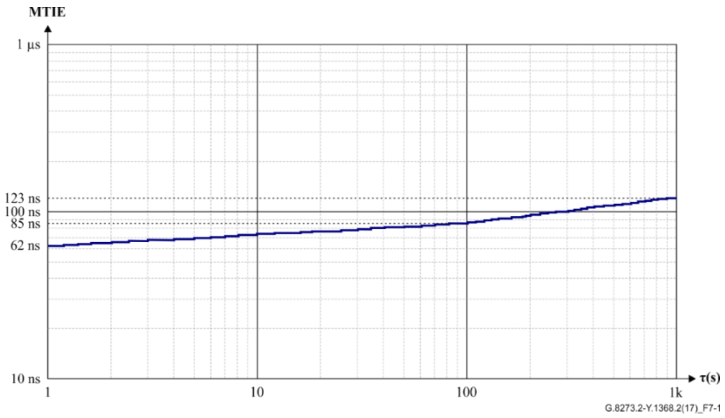


Figure 11: SyncE-assisted holdover performance

Figure 12 shows how the holdover performance can be measured. The flow of PTP packets is interrupted, and the output drift measured for a period following the loss of packets. The SyncE frequency reference should be "ideal" during the test, i.e. phase wander as low as possible.

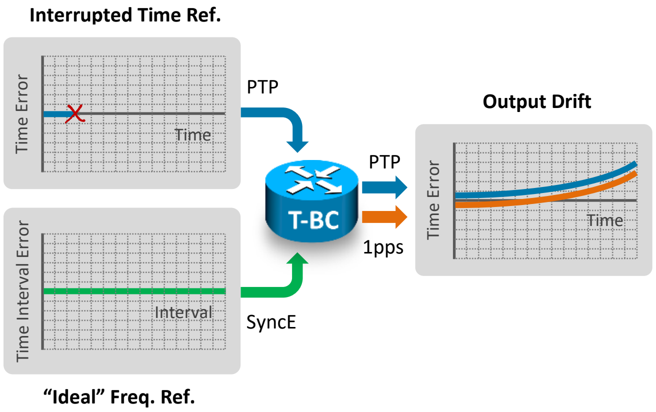


Figure 12: T-BC Holdover Measurement

3. Further Reading

The following documents contain the various clock specifications defined by the ITU-T:

1. ITU-T Recommendation G.8260: "Definitions and terminology for synchronization in packet networks", Edition 3.1, August 2015
2. ITU-T Recommendation G.8262: "Timing characteristics of a synchronous Ethernet equipment slave clock", Edition 3, January 2015
3. ITU-T Recommendation G.8271.1: "Network limits for time synchronization in packet networks", Edition 2, October 2017
4. ITU-T Recommendation G.8273: "Framework of Phase and Time Clocks", Edition 1.1, August 2014, plus Amendment 1 (January 2015) and Amendment 2 (August 2015)
5. ITU-T Recommendation G.8273.2: "Timing characteristics of telecom boundary clocks", Edition 3, August 2019
6. ITU-T Recommendation G.8275.1: "Precision time protocol telecom profile for phase/time synchronization with full timing support from the network", Edition 2, June 2016

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CX6001 v1.1 Jan 2020