Evaluating PTP time clock performance

T-BC and T-TSC requirements and performance metrics

Application note

Contents

Introduction

Recommendation ITU-T G.8273.2 [1] is one of the most important recommendations for ensuring accurate phase and time synchronization over a packet network. It specifies the minimum clock performance requirements for telecom boundary clocks (T-BC) and telecom time synchronous clocks (T-TSC) when they are deployed with full timing support from the network, i.e., when phase/time synchronization is provided by all T-BCs and T-TSCs with underlying physical layer frequency support.

The recommendation specifies the following performance requirements for T-BC and T-TSC:

- Time error noise generation
- Noise tolerance
- Noise transfer
- Transient response
- Holdover performance

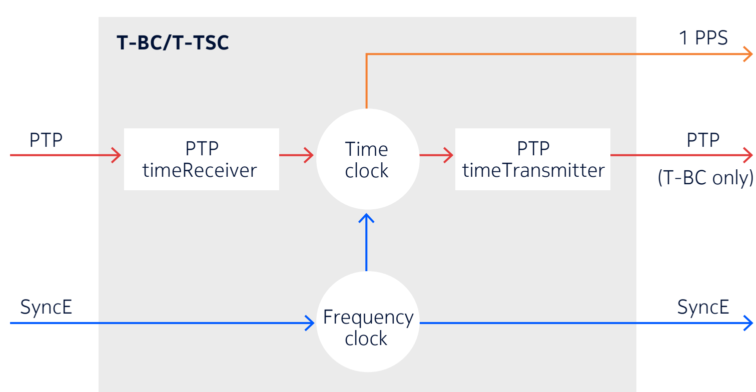
The telecommunications industry tends to focus exclusively on time error noise generation because it is the easiest to understand and most frequently used to compare with time error budget in networks. However, the other metrics are also important. Network operators and service providers must analyze all five metrics when they assess synchronization solutions. A statement of compliance in an RFP/RFQ should ask for conformance to the five metrics, rather than only the time noise generation metric and the associated class.

This application note explains these performance requirements and assesses their relative importance. It is not a test methodology guide. For this guidance on testing, refer to application notes from test equipment vendors such as Calnex [2].

ITU-T G.8273.2 performance requirements

Figure 1 illustrates a simplified model of a T-BC/T-TSC with full timing support, as described in Appendix III of ITU-T G.8273.2. The model is composed of two clocks: a time clock and a frequency clock. The time clock is locked to the Precision Time Protocol (PTP) time input, and the frequency clock is locked to the physical layer frequency input (e.g., SyncE, SDH, BITS). The frequency clock can be an SDH Equipment Clock (SEC, now renamed Synchronous Equipment Clock), synchronous Ethernet Equipment Clock (EEC), or enhanced EEC (eEEC), as defined respectively in recommendations ITU-T G.813 [3], ITU-T G.8262 [4] and ITU-T G.8262.1 [5].

Figure 1. Simplified model of a T-BC/T-TSC



Recommendation ITU-T G.8273.2 defines the performance requirements for T-BCs and T-TSCs in terms of five main metrics, as listed in the introduction.

It is important to note that the values given in ITU-T G.8273.2 are not for an entire network. Recommendation ITU-T G.8273.2 is a clock specification, i.e., it specifies the performance of a specific clock, or a single network element (NE). It is not applicable to a network composed of multiple NEs. For an estimation of maximum time error accumulated in a chain of T-BCs, mathematical calculations are needed, for which Nokia has developed a comprehensive analysis calculator and can provide guidance.

To support different use cases with different performance requirements for the end application, this recommendation categorizes T-BCs and T-TSCs into classes A, B, C and D, in order of increasing accuracy. The classes were introduced initially for the time error noise generation metric, while the other performance metrics remained common for all classes. As the recommendation has evolved, some specification differences are now introduced for other metrics, such as transient response and holdover.

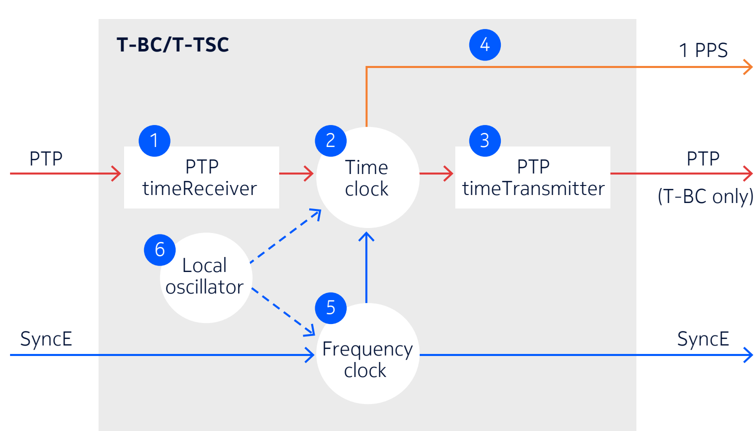
The class A and B clocks are intended to be deployed together with Synchronous Ethernet (SyncE), defined in ITU-T G.8262, and are typically the class of performance required for mobile backhaul applications. The class C and D clocks were developed based on simulations that assume deployment with Enhanced Synchronous Ethernet (eSyncE), defined in ITU-T G.8262.1. Class C is required for mobile fronthaul applications as well as other specific applications that require more stringent time synchronization (e.g., E911 OTDOA). However, 3GPP has not officially identified backhaul applications that require this level of accuracy.

Clock accuracy is important for deployment and time error budget planning. The better the clock accuracy, the more clock instances possible in the synchronization chain without exceeding the end-to-end budget limits for the time error accumulation. This allows for more economical and practical deployments with more centralized telecom grandmaster (T-GM) pools rather than distributing many expensive edge T-GMs. The time error delivered to an end application of the clock chain can be minimized by utilizing clocks with a lower contribution to the overall time error.

Time error noise generation

In terms of a PTP time clock, the term “noise” means “time error.” Time error is the difference between the time value produced by the T-BC or T-TSC and the time of the reference clock from the associated time transmitter clock. For illustration purposes, Figure 2 shows the contributors in a T-BC or T-TSC that can generate time error and pass it on to the downstream clocks. The clock time error is a combination of all the mentioned possibilities, and the performance is measured at the output interfaces.

Figure 2. Contributors to time error in a T-BC/T-TSC

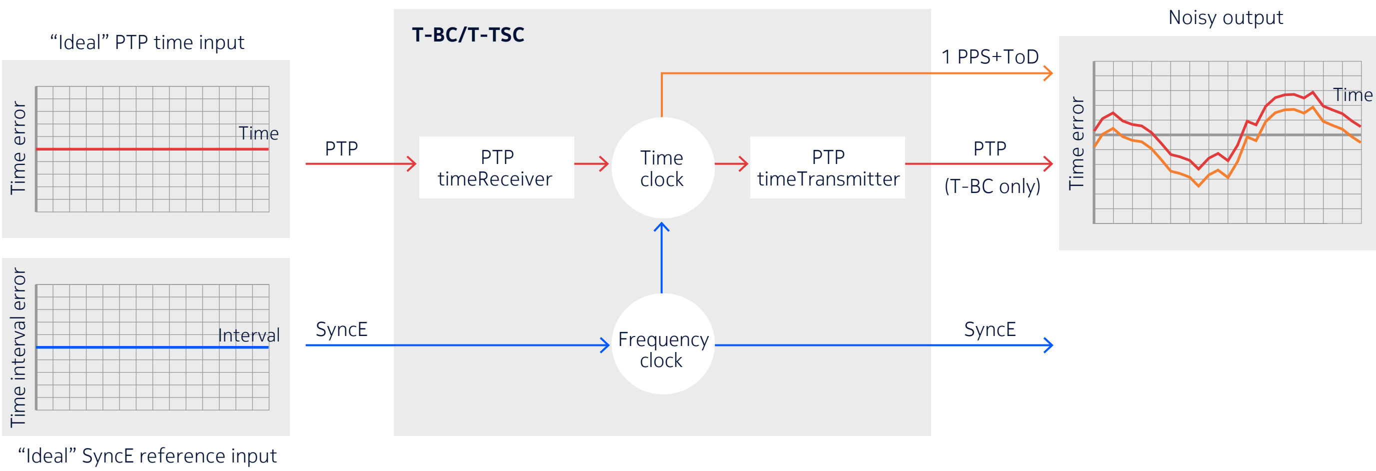


The contributors to time error are listed below, with the numbers matching those in the figure:

1. Timestamping time error at the PTP timeReceiver port
2. Time error introduced within the time clock
3. Timestamping time error at the PTP timeTransmitter port
4. Time error introduced in the 1 PPS output
5. Noise from the SyncE frequency reference
6. Phase noise introduced by the local oscillator

The time error noise generation of a T-BC or T-TSC represents the amount of time error produced at the output of a clock when it is fed with an ideal PTP time reference input and an ideal frequency reference input, as shown in Figure 3.

Figure 3. T-BC/T-TSC noise generation



As shown in Figure 4, the time error performance requirements for T-BCs and T-TSCs are specified in three parameters that include the following set of sub-metrics:

- **Maximum absolute time error (max|TE|)** is defined as the maximum absolute value of the time error function of the T-BC/T-TSC. The max|TE| represents the maximum amount of noise that may be generated by the clock, which includes cTE and dTE. For a network limit, the max|TE| represents the maximum noise allowed to accumulate in the network, which would be used for specifying the next hop's clock noise tolerance.
- **Constant time error (cTE)** is the mean of the time error function of the T-BC/T-TSC, measured over a long observation interval, i.e., 1,000 seconds. The cTE represents the asymmetry contributed by the clock, which cannot be removed by filtering. In a network limit, cTE is typically not specified, since it is constrained by the max|TE|, which includes cTE and dTE.
- **Dynamic time error (dTE)** is the change of the time error function of the T-BC/T-TSC over time. This is normally characterized using time interval error (TIE) and compared to a mask expressed either in maximum time interval error (MTIE) or time deviation (TDEV). The dTE is further divided into dynamic time error low-pass filtered noise generation (dTE_L) and dynamic time error high-pass filtered noise generation (dTE_H). In a clock specification, dTE represents a stability constraint on a clock. When used as a network limit, dTE represents the overall stability of the network.

Figure 4. max|TE|, cTE and dTE definitions

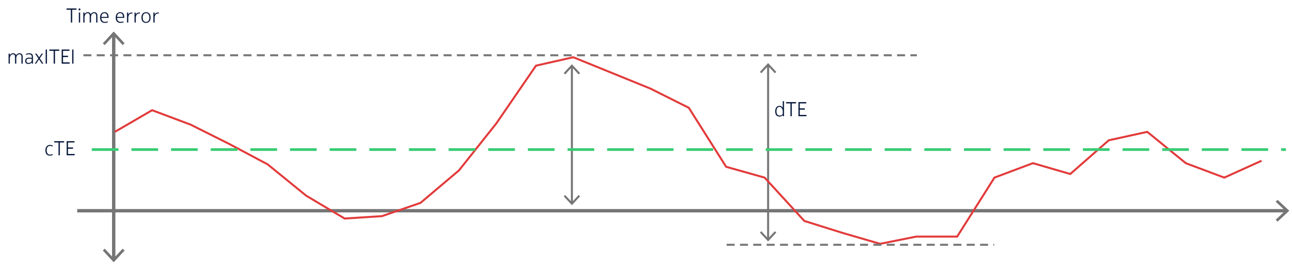


Table 1 shows the performance requirements of max|TE|, cTE, dTE_L and dTE_H for T-BC/T-TSC, which are all specified for classes A, B and C in ITU-T G.8273.2 clause 7.1. The requirements for class D are for further study (FFS). For class D, only a new metric, maximum time error low-pass filtered ($max|TE_L|$), is defined. This indicates that class D is not fully specified. Unless the vendor and service providers can agree on specific values for the other metrics, class D should not be used. There are currently no real applications that demand this level of accuracy.

Table 1. Time error noise generation performance requirements for each class of ITU-T G.8273.2 PTP

Performance metric	Class A	Class B	Class C	Class D
max|TE|	100 ns	70 ns	30 ns	FFS
$max\|TE_L\|$	—	—	—	5 ns
cTE	±50 ns	±20 ns	±10 ns	FFS
dTE_L MTIE	40 ns	40 ns	10 ns	FFS
dTE_L TDEV	4 ns	4 ns	2 ns	FFS
dTE_H	70 ns	70 ns	30 ns	FFS
Note: FFS means "for further study."				

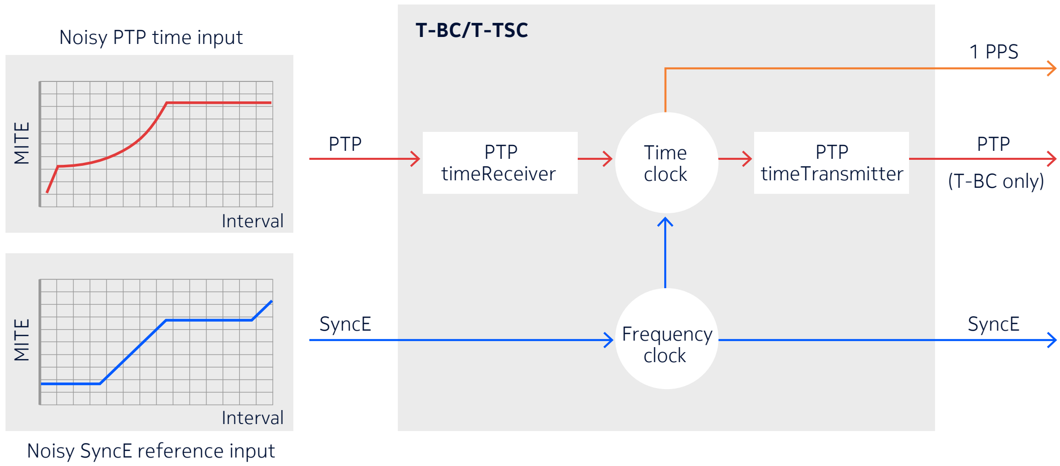
More recently, ITU-T G.8273.2 added the definition of relative time error (TE_R) for class C clocks, in clause 7.1.4. This metric is for the time error between interfaces of the same T-BC/T-TSC. It also includes limits for $max|TE_R|$, cTE_R and dTE_{RL}. The metric was added for testing purposes and in support of the relative time error calculations in fronthaul as defined in 3GPP, the O-RAN WG4 CUS specification [6] and IEEE Std 802.1CM [7].

This set of noise generation performance metrics is clearly the most critical for time error budgeting and planning in end-to-end synchronization network design. As described in ITU-T G.8271 [8], different applications have different accuracy class levels for time and phase synchronization. Time error is used to specify the requirements for these class levels. Compliance with these requirements is critical for ensuring high application performance.

Noise tolerance

The time noise tolerance of a T-BC or T-TSC defines how much noise it can tolerate on its input and still be able to maintain its normal working function without raising alarms, switching to another reference input or going into holdover state. Time noise tolerance is measured by adding a noisy signal to the PTP and SyncE input ports, as shown in Figure 5.

Figure 5. T-BC/T-TSC noise tolerance



The noise tolerance performance requirements for T-BC/T-TSC classes A, B and C are specified in ITU-T G.8273.2 clause 7.2. For the PTP input, noise tolerance is defined in terms of the maximum dTE of the input signal based on network limits specified in ITU-T G.8271.1 clause 7.3. For SyncE input, the wander tolerance for T-BC/T-TSC classes A and B at the synchronous equipment clock input is described in ITU-T G.8262 clause 9.1.1. The wander tolerance for T-BC/T-TSC class C at the eEEC input is defined in ITU-T G.8262.1 clause 9. The requirements for class D are for further study.

As with all metrics, noise tolerance should be tested. But meeting this performance metric will depend on network design and may be more negotiable. It is unlikely that a properly designed network PTP/SyncE chain will be pushed to this limit. The requirement is to avoid alarms and reference switching or entering holdover. It is not difficult to meet through network design. Even if the mask is exceeded, there is sufficient wiggle room to accommodate a bit of margin beyond the standard's limit before the operator sees an impact on end-application performance.

Noise transfer

The time noise transfer characteristic of the T-BC/T-TSC is determined by how much time error noise present at the input is transferred to the output of the PTP clock. There are five possible timing flows in a T-BC/T-TSC, which are listed below and illustrated in Figure 6. The frequency and time domains have to be considered, as do the interactions between them because they can transfer noise from the input to the output. Each flow has an associated bandwidth and gain peak limit that defines the characteristics of the filter in the path. The noise transfer performance is defined in the standard for the timing flows enumerated below.

1) PTP input to 1 PPS time/phase output

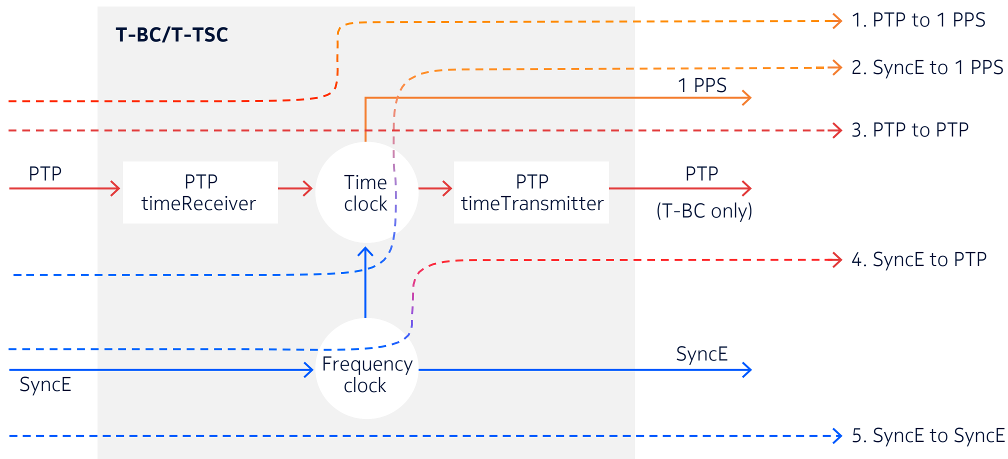
2) SyncE input to 1 PPS output

3) PTP input to PTP time/phase output

4) SyncE input to PTP time/phase output

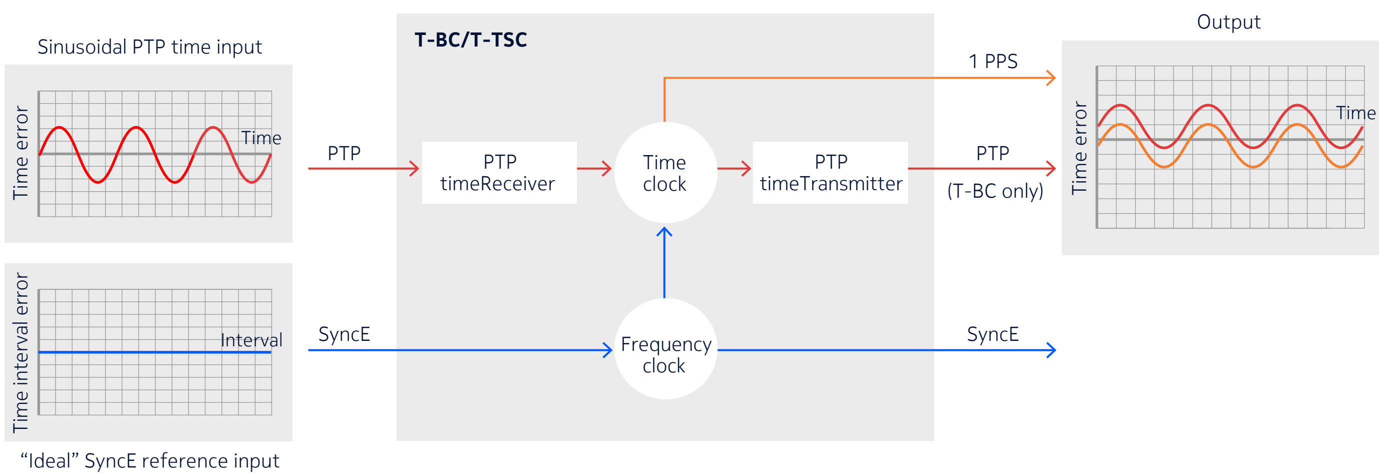
5) SyncE input to SyncE output

Figure 6. T-BC/T-TSC timing flows impacting noise transfer



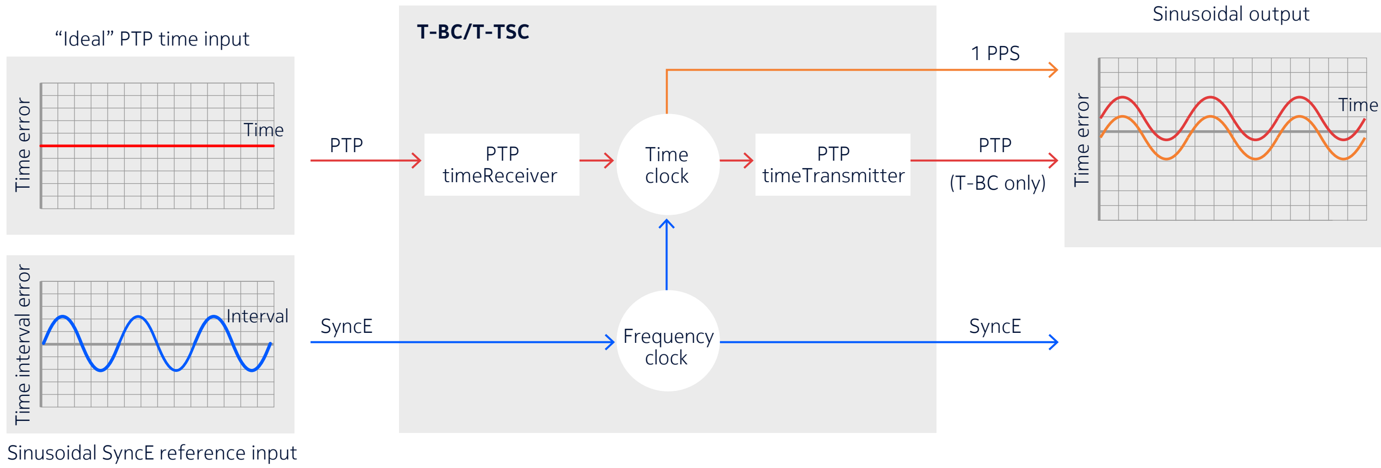
To measure the noise transfer of timing flows 1 and 3 for a T-BC/T-TSC, i.e., PTP input to PTP or 1 PSS output, a sinusoidal PTP time signal and an ideal SyncE reference signal are inserted on the PTP input and SyncE input, respectively, as illustrated in Figure 7. The noise transferred by the clock is then measured at the output.

Figure 7. T-BC/T-TSC noise transfer—PTP input to PTP output



To measure the noise transfer of timing flows 2 and 4 for a T-BC/T-TSC, i.e., SyncE input to PTP or 1 PPS output, as shown in Figure 8, a sinusoidal SyncE reference signal and an ideal PTP time signal are inserted on the SyncE and PTP inputs, respectively.

Figure 8. T-BC/T-TSC noise transfer—SyncE input to PTP output



The noise presented on the input will be transferred to the output after the clock has filtered the noise. Time noise transfer requirements are defined in ITU-T G.8273.2 clause 7.3 for the following transfer functions:

- **PTP input to PTP (and 1 PPS) output**: The low-pass filter has a bandwidth between 0.05 Hz and 0.1 Hz. In the passband, the phase gain should be smaller than 0.1 dB.
- **Physical layer frequency input to PTP (and 1 PPS) output for T-BC/T-TSC classes A and B**: The band-pass filter has a frequency between 0.05 Hz and 0.1 Hz at the lower corner and between 1 Hz and 10 Hz at the upper corner. In the passband, the phase gain should be smaller than 0.2 dB.
- **Physical layer frequency input to PTP (and 1 PPS) output for T-BC/T-TSC classes C and D**: The band-pass filter has a frequency between 0.05 Hz and 0.1 Hz at the lower corner and between 1 Hz and 3 Hz at the upper corner. In the passband, the phase gain should be smaller than 0.2 dB.

The filtering ability of a clock determines the amount of noise transferred through the clock from input to output. Obviously, less noise transfer is preferred. This metric is important because it has an impact on the normal operation of the active chain. Each node must control its noise contribution to the whole chain. Noise transfer is a good example of a metric that can only be measured on a single device under test (DUT), i.e., a single clock. End-to-end network testing is not sufficient.

Transient response

The time transient response is the reaction of a PTP clock following the rearrangement of the PTP network or the physical layer frequency reference (e.g., SyncE). Rearrangement of the PTP network occurs, for example, if failures lead to the recalculation of a new path by the alternate Best TimeTransmitter Clock Algorithm (BTCA). This will cause the current PTP time reference to switch to an alternate reference. Similarly, rearrangement of the physical layer frequency reference occurs if there is a frequency reference switchover caused, for example, by a failure or change of the received quality level (QL) while another reference still receives a better QL.

The PTP/1 PPS output transient response requirements for T-BC/T-TSC are defined in ITU-T G.8273.2 clause 7.4.1. This clause provides requirements for classes A, B and C in the case of rearrangement of the physical layer frequency reference, and for class C in the case of long-term rearrangement (holdover) of the physical layer frequency reference as defined in ITU-T G.8273.2. The requirements for the following scenarios are for further study at the time of writing this document:

- Simultaneous rearrangement of the physical layer frequency reference and PTP network simultaneously
- Rearrangement of the PTP network only
- Rearrangement of the physical layer frequency reference only for T-BC/T-TSC class D
- Long-term rearrangement of the physical layer frequency reference only for T-BC/T-TSC classes A, B and D.

As for previously presented metrics other than time noise generation, the requirements for class D are all for further study.

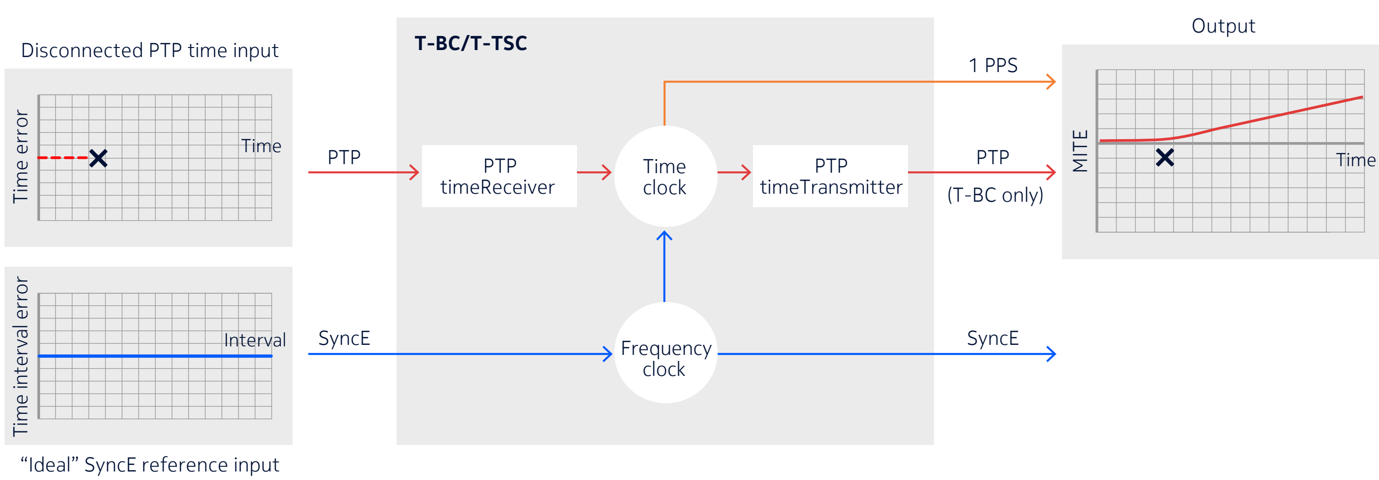
Since synchronization is extremely important and often a matter of national security, synchronization networks are built with high resiliency and redundancy. These networks are designed and deployed with multiple references to a clock and provide redundancy and backup for timing synchronization in case of reference failure or degradation. The behavior of the PTP clock and its impact on the network during reference switching are important, which means the transient response performance metric is very important. This requirement must always be met and should be considered mandatory.

Holdover performance

Holdover is one of the most well-known frequency performance metrics in Synchronous Digital Hierarchy (SDH) and SyncE. It also exists for PTP time/phase distribution. The requirement of holdover for T-BC/T-TSC are specified in ITU-T G.8273.2 clause 7.4.2. Time holdover, sometimes called long-term rearrangement, defines the maximum excursion in the PTP and 1 PPS output signal if the PTP timing input or physical layer frequency input is lost. There are two types of holdovers for T-BC/T-TSC depending on whether SyncE assistance is supported: loss of PTP input only, and loss of PTP input and SyncE input simultaneously.

For the first use case, where only the PTP input is lost, the SyncE reference is still traceable to a primary reference clock (PRC), as shown in Figure 9. The SyncE frequency-assisted holdover helps maintain the time base of the clock. If the frequency reference remains traceable to a PRC, it will maintain accurate phase/time and extend the duration of holdover within the time error limits specified in ITU-T G.8271.1 [9]. This improves the holdover performance for this failure case. The holdover capability allows more time for troubleshooting and provides uninterrupted service during the holdover periods. The requirements for T-BC/T-TSC class A and B holdover performance with physical layer frequency assistance during loss of PTP input reference are defined in this recommendation. For classes C and D, the requirements are for further study.

Figure 9. T-BC/T-TSC SyncE-assisted holdover performance



In the second case, where both PTP input and SyncE input are lost, the clock can rely only on its internal oscillator to maintain the output time performance during its holdover period. Unfortunately, the requirements for this use case are still for further study in ITU-T G.8273.2. This is probably the most plausible use case because a link failure will cause loss of both SyncE and PTP inputs simultaneously in congruent SyncE/PTP network designs. It is advisable to ask for the performance specification in this case. The holdover performance metric is obviously an important one, but as currently specified, it is probably less important than time noise generation and transient response.

Conclusion

This application note has explained the performance requirements and metrics defined in recommendation ITU-T G.8273.2 and noted their importance for network operators and service providers, as summarized in Table 2 below. Operators and providers should measure all of these metrics when they benchmark solutions.

Table 2. Summary of ITU-T G.8273.2 performance metrics

Metric	Clause	Importance
Time error noise generation	7.1	High
Noise tolerance	7.2	Low
Noise transfer	7.3	Medium
Transient response	7.4.1	High
Holdover performance	7.4.2	High

References

[1] ITU-T G.8273.2, Timing characteristics of telecom boundary clocks and telecom time slave clocks for use with full timing support from the network, Amendment 1, August 2024

[2] Calnex Test Guide CX3009 - G.8273.2 BC Conformance Test Guide at https://calnexsol.com/

[3] ITU-T G.813, Timing characteristics of SDH equipment slave clocks (SEC), March 2003

[4] ITU-T G.8262, Timing characteristics of a synchronous equipment slave clock, Amendment 1, March 2020

[5] ITU-T G.8262.1, Timing characteristics of enhanced synchronous equipment slave clock, November 2022

[6] O-RAN.WG4.CUS.0-R003-v15.00 - O-RAN Control, User and Synchronization Plane Specification 15.0, June 2024

[7] IEEE Std 802.1CM-2018 IEEE Standard for Local and metropolitan area networks— Time-Sensitive Networking for Fronthaul, amended by IEEE Std 802.1CMde-2020

[8] ITU-T G.8271 Time and phase synchronization aspects of telecommunication networks, Amendment 1, August 2024

[9] ITU-T G.8271.1, Network limits for time synchronization in packet networks with full timing support from the network, Amendment 2, January 2024

Abbreviations

1 PPS	one pulse per second
BITS	building integrated timing supply
BTCA	Best TimeTransmitter Clock Algorithm
cTE	constant time error
dTE	dynamic time error
DUT	device under test
E911	Enhanced 911
EEC	synchronous Ethernet Equipment Clock
eEEC	enhanced synchronous Ethernet Equipment Clock
eSyncE	Enhanced Synchronous Ethernet
FFS	for further study
max|TE|	maximum absolute time error
MTIE	maximum time interval error
NE	network element
OTDOA	observed time difference of arrival
PRC	primary reference clock
PTP	Precision Time Protocol
QL	quality level
RFP	request for proposal
RFQ	request for quotation
SDH	Synchronous Digital Hierarchy
SEC	Synchronous Equipment Clock
SyncE	Synchronous Ethernet
T-BC	telecom boundary clock
TDEV	time deviation
TE	time error
T-GM	telecom grandmaster
TIE	time interval error
T-TSC	telecom time synchronous clock

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