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ITU-T   G.8271.1/Y.1366.1

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Amendment 1
(03/2018)

SERIES G: TRANSMISSION SYSTEMS AND MEDIA, DIGITAL SYSTEMS AND NETWORKS

Packet over Transport aspects – Synchronization, quality and availability targets

SERIES Y: GLOBAL INFORMATION INFRASTRUCTURE, INTERNET PROTOCOL ASPECTS, NEXT-GENERATION NETWORKS, INTERNET OF THINGS AND SMART CITIES

Internet protocol aspects – Transport

Network limits for time synchronization in packet networks

Amendment 1

Recommendation ITU-T G.8271.1/Y.1366.1 (2017) – Amendment 1

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Recommendation ITU-T G.8271.1/Y.1366.1

Network limits for time synchronization in packet networks

Amendment 1

Summary

Recommendation ITU-T G.8271.1/Y.1366.1 specifies the maximum network limits of phase and time error that shall not be exceeded. It specifies the minimum equipment tolerance to phase and time error that shall be provided at the boundary of packet networks at phase and time synchronization interfaces. It also outlines the minimum requirements for the synchronization function of network elements.

This Recommendation addresses the case of time and phase distribution across a network by a packet-based method with full timing support to the protocol level from the network.

Amendment 1 provides the following updates:

- changes to clause 7 (Network limits);
- minor enhancements to Appendix III;
- amendment to Appendix V;
- replacement of Appendix VII;
- replacement of Figure IX.1;
- addition of new Appendix X;
- addition of new Appendix XI;
- addition of a Bibliography.

History

Edition	Recommendation	Approval	Study Group	Unique ID[*]
1.0	ITU-T G.8271.1/Y.1366.1	2013-08-29	15	11.1002/1000/12034
1.1	ITU-T G.8271.1/Y.1366.1 (2013) Amd. 1	2014-05-14	15	11.1002/1000/12194
1.2	ITU-T G.8271.1/Y.1366.1 (2013) Amd. 2	2015-01-13	15	11.1002/1000/12392
2.0	ITU-T G.8271.1/Y.1366.1	2017-10-07	15	11.1002/1000/13323
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Keywords

Full timing support, network limits, precision time protocol, phase, synchronization, time.

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FOREWORD

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The World Telecommunication Standardization Assembly (WTSA), which meets every four years, establishes the topics for study by the ITU-T study groups which, in turn, produce Recommendations on these topics.

The approval of ITU-T Recommendations is covered by the procedure laid down in WTSA Resolution 1.

In some areas of information technology which fall within ITU-T's purview, the necessary standards are prepared on a collaborative basis with ISO and IEC.

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In this Recommendation, the expression "Administration" is used for conciseness to indicate both a telecommunication administration and a recognized operating agency.

Compliance with this Recommendation is voluntary. However, the Recommendation may contain certain mandatory provisions (to ensure, e.g., interoperability or applicability) and compliance with the Recommendation is achieved when all of these mandatory provisions are met. The words "shall" or some other obligatory language such as "must" and the negative equivalents are used to express requirements. The use of such words does not suggest that compliance with the Recommendation is required of any party.

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As of the date of approval of this Recommendation, ITU had not received notice of intellectual property, protected by patents, which may be required to implement this Recommendation. However, implementers are cautioned that this may not represent the latest information and are therefore strongly urged to consult the TSB patent database at http://www.itu.int/ITU-T/ipr/.

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Network limits for time synchronization in packet networks

Amendment 1

Editorial note: This is a complete-text publication. Modifications introduced by this amendment are shown in revision marks relative to Recommendation ITU-T G.8271.1/Y.1366.1 (2017).

1 Scope

This Recommendation specifies the maximum network limits of phase and time error that shall not be exceeded. It specifies the minimum equipment tolerance to phase and time error that shall be provided at the boundary of packet networks at phase and time synchronization interfaces. It also outlines the minimum requirements for the synchronization function of network elements.

This Recommendation addresses the case of time and phase distribution across a network with packet-based method with full timing support to the protocol level from the network.

The physical layer (PHY) that is relevant to this specification is the Ethernet media type as defined in [IEEE 802.3-2015].

2 References

The following ITU-T Recommendations and other references contain provisions which, through reference in this text, constitute provisions of this Recommendation. At the time of publication, the editions indicated were valid. All Recommendations and other references are subject to revision; users of this Recommendation are therefore encouraged to investigate the possibility of applying the most recent edition of the Recommendations and other references listed below. A list of the currently valid ITU-T Recommendations is regularly published. The reference to a document within this Recommendation does not give it, as a stand-alone document, the status of a Recommendation.

[ITU-T G.803]	Recommendation ITU-T G.803 (2000), *Architecture of transport networks based on the synchronous digital hierarchy (SDH)*.
[ITU-T G.810]	Recommendation ITU-T G.810 (1996), *Definitions and terminology for synchronization networks*.
[ITU-T G.812]	Recommendation ITU-T G.812 (2004), *Timing requirements of slave clocks suitable for use as node clocks in synchronization networks*.
[ITU-T G.823]	Recommendation ITU-T G.823 (2000), *The control of jitter and wander within digital networks which are based on the 2048 kbit/s hierarchy*.
[ITU-T G.8260]	Recommendation ITU-T G.8260 (2015), *Definitions and terminology for synchronization in packet networks*.
[ITU-T G.8262]	Recommendation ITU-T G.8262/Y.1362 (2015), *Timing characteristics of a synchronous Ethernet equipment slave clock*.
[ITU-T G.8271]	Recommendation ITU-T G.8271/Y.1366 (2017), *Time and phase synchronization aspects of telecommunication networks*.
[ITU-T G.8272]	Recommendation ITU-T G.8272/Y.1367 (2015), *Timing characteristics of primary reference time clocks*.
[ITU-T G.8273]	Recommendation ITU-T G.8273/Y.1368 (2013), *Framework of phase and time clocks*.

[ITU-T G.8273.2]   Recommendation ITU-T G.8273.2/Y.1368.2 (2017), *Timing characteristics of telecom boundary clocks and telecom time slave clocks*.

[ITU-T G.8275]   Recommendation ITU-T G.8275/Y.1369 (2017), *Architecture and requirements for packet-based time and phase distribution*.

[IEEE 802.3-2015]   IEEE 802.3-2015, *IEEE standard for Ethernet*.

[IEEE 1588-2008]   IEEE 1588-2008, IEEE *standard for a precision clock synchronization protocol for networked measurement and control systems*.

3   Definitions

3.1   Terms defined elsewhere

This Recommendation uses the terms and definitions contained in [ITU-T G.810] and [ITU-T G.8260].

3.2   Terms defined in this Recommendation

None.

4   Abbreviations and acronyms

This Recommendation uses the following abbreviations and acronyms:

CPRI   Common Public Radio Interface

DSLAM   Digital Subscriber Line Access Multiplexer

EEC   Ethernet Equipment Clock

GNSS   Global Navigation Satellite System

GPON   Gigabit-capable Passive Optical Network

HRM   Hypothetical Reference Model

LTE   Long-Term Evolution

MTIE   Maximum Time Interval Error

OLT   Optical Line Terminal

ONT   Optical Network Terminal

OSC   Optical Supervisory Channel

OTN   Optical Transport Network

PHY   Physical layer

PLL   Phase-Locked Loop

PPS   Pulse Per Second

PRC   Primary Reference Clock

PRTC   Primary Reference Time Clock

PTP   Precision Time Protocol

RE   Radio Equipment

REC   Radio Equipment Control

RT-DSLAM   Remote Terminal-Digital Subscriber Line Access Multiplexer

SDH	Synchronous Digital Hierarchy
SSM	Synchronization Status Message
SSU	Synchronization Supply Unit
T-BC	Telecom Boundary Clock
TDD	Time Division Duplex
TDEV	Time Deviation
TE	Time Error
T-GM	Telecom Grand Master
T-TC	Telecom Transparent Clock
T-TSC	Telecom Time Slave Clock
VCO	Voltage Controlled Oscillator
xDSL	x-type Digital Subscriber Line
xPON	x Passive Optical Network

5 Conventions

Within this Recommendation, the following conventions are used: the term precision time protocol (PTP) refers to the PTP protocol defined in [IEEE 1588-2008].

The terms dynamic time error (TE) and time noise are used interchangeably throughout this Recommendation to indicate jitter and wander components of the timing signal.

6 Network reference model

The general network reference model is described in [ITU-T G.8271].

7 Network limits

The following main (i.e., worst case) scenarios have been identified and are considered in the definition of the relevant network limits:

– deployment case 1: time distribution chain with telecom time slave clock (T-TSC) integrated into the end application and end application with a distributed architecture.

   In this case, the performance specification of the T-TSC is outside the scope of [ITU-T G.8273.2].

– deployment case 2: time distribution chain with a T-TSC external to the end application and end application with a distributed architecture.

   NOTE – a specific equipment implementation may also be based on implementing a telecom boundary clock (T-BC) function (instead of a T-TSC function) and delivering the phase/time reference to the end application via a phase/time synchronization distribution interface.

   In this case, the performance specification of the T-TSC is defined in [ITU-T G.8273.2].

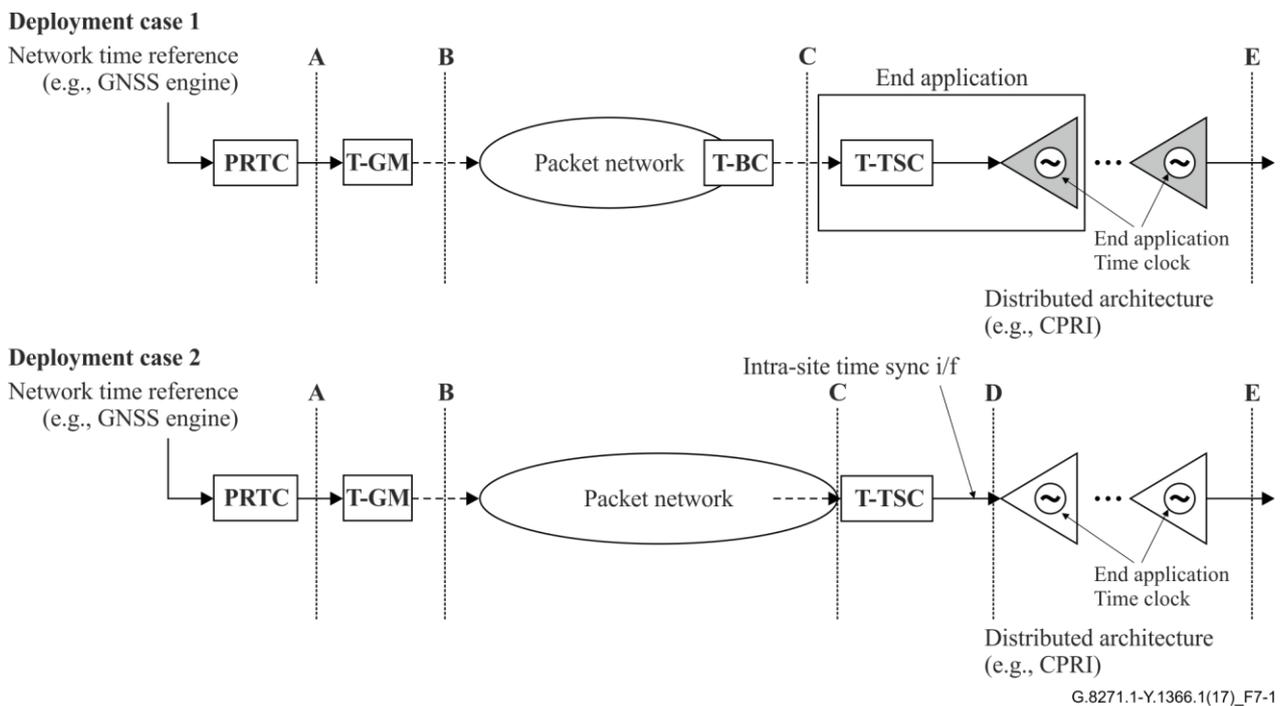The deployment cases are shown in Figure 7-1.

Figure 7-1 – Time synchronization deployment cases

NOTE 1 – An example of distributed architecture is the case of mobile applications where the base stations have the base band unit [also called radio equipment control (REC)] connected remotely to the radio units [also called radio equipment (RE)]. In this case, a point to point connection (e.g., via fibre) is assumed and chain topologies are possible. The TE budget applicable to this connection is assumed to be 150 ns; the details on the chain topology are for further study.

NOTE 2 – The network limit applicable at reference point E is defined by the specific application as per Table 1 of [ITU-T G.8271]. The applications corresponding to the class 4 (1.5 microseconds), according to Table 1 of [ITU-T G.8271] are currently considered in this Recommendation.

7.1 Network limits at reference point A

The network limits applicable at reference point A, i.e., at the output of the primary reference time clock (PRTC), are specified in [ITU-T G.8272]. In particular, according to [ITU-T G.8272], the maximum absolute TE is:

$$|TE| \leq 100 \text{ ns}$$

NOTE – This limit is applicable under normal, locked operating conditions. The limit under failure conditions at the PRTC is for further study.

Dynamic TE network limits applicable at reference point A are also specified in [ITU-T G.8272].

7.2 Network limits at reference point B

In the case of a telecom grand master (T-GM) integrated into the PRTC, the network limits applicable at reference point B are the same as the limits applicable at reference point A.

In the case of a T-GM external to the PRTC, the network limits applicable at reference point B are for further study.

7.3 Network limits at reference point C

The limits given in this clause represent the maximum permissible levels of phase/time error and noise at interfaces within a packet network in charge of distributing phase/time synchronization according to the applications corresponding to class 4 listed in Table 1 of [ITU-T G.8271].

The limits applicable to other classes at the reference point C are for further study.

The noise generated by a chain of T-BC or telecom transparent clock (T-TC) is characterized by two main aspects:

1)   the constant TE produced by the chain, e.g., due to various fixed and uncompensated asymmetries (including the PRTC);

2)   the dynamic TE produced by the various components of the chain (including the PRTC) – this noise can be classified as low or high frequency noise, with components below or above 0.1 Hz, respectively.

The network limits applicable at reference point C are expressed in terms of two quantities:

1)   the maximum absolute TE: max $|TE|$, which includes the constant TE and the low frequency components of the dynamic TE;

2)   a suitable metric applied to the dynamic TE component (in particular, maximum time interval error (MTIE) and time deviation (TDEV) are used to measure noise components with frequencies lower than 0.1 Hz, and peak-to-peak TE is used for measuring noise components with frequency higher than 0.1 Hz).

The limits given in the following shall be met for all operating conditions (except during PTP rearrangements and long holdover conditions in the network and during both PTP and the PHY frequency rearrangements conditions that are for further study; see also examples in Appendix V), regardless of the amount of equipment preceding the interface. In general, these network limits are compatible with the minimum tolerance to TE and noise that all equipment input ports are required to provide. Further guidance about how to design a phase/time distribution network is provided in Appendix V.

For deployment case 1, the network limits applicable at reference point C are:

–   maximum absolute TE network limit, max $|TE| \leq 1\ 100$ ns;

–   Dynamic low frequency TE network limit: the specification in terms of MTIE is presented in Table 7-1 and Figure 7-2; the specification in terms of TDEV is for further study.

Table 7-1 – Dynamic time error network limit expressed in MTIE

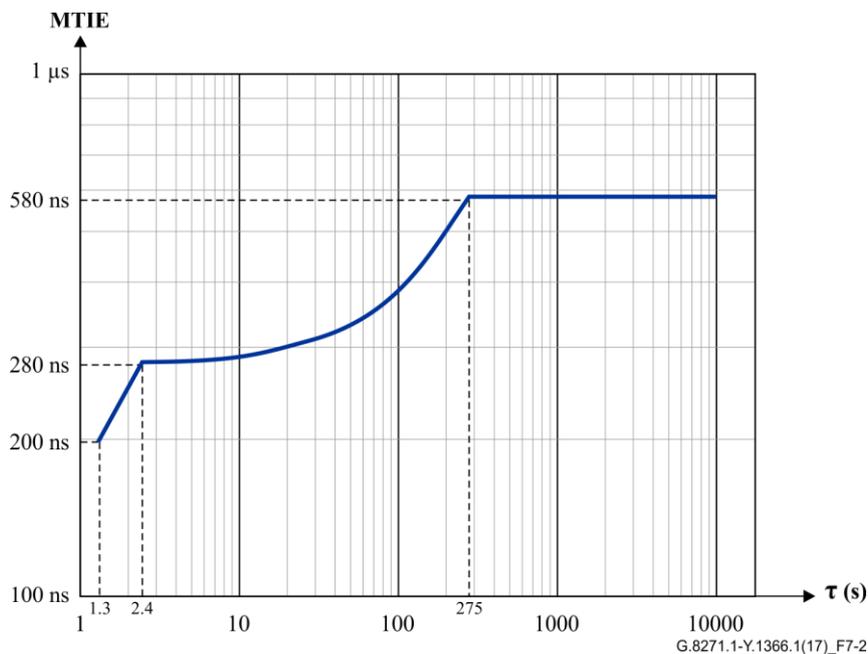| MTIE limit (ns)	Observation interval, τ (s)
$100 + 75\tau$	$1.3 < \tau \leq 2.4$
$277 + 1.1\tau$	$2.4 < \tau \leq 275$
580	$275 < \tau \leq 10\ 000$

Figure 7-2 – Dynamic time error network limit (MTIE)

A first-order low-pass measurement filter with bandwidth of 0.1 Hz is applied to the TE samples measured at the packet timing interface prior to evaluating the max |*TE*|, MTIE and TDEV. Network limits measurements performed on the 1 pulse per second (PPS) test output should also perform a similar filtering on the 1 PPS signal.

Additional details on the test equipment characteristics and measurement period are also for further study.

NOTE – The above MTIE specification is the result of a number of conservative assumptions that, in theory, may lead to a dynamic component with max |*TE*| greater than 300 ns and frequency components less than 0.1 Hz. However, the related dynamic noise component has been demonstrated to have max |*TE*| that is always less than 300 ns under the assumptions made in this Recommendation and other related Recommendations, e.g., [ITU-T G.8273.2].

The following requirement applies for frequency components higher than 0.1 Hz (a first-order high-pass filter with bandwidth of 0.1 Hz should be applied to the TE samples measured at the packet timing interface or to the 1 PPS signal), as measured over a 10 000 s interval:

–   peak-to-peak TE amplitude < 200 ns

For deployment case 2, the network limits applicable at reference point C are for further study.

7.4   Network limit at reference point D

In deployment case 1, reference point D might not be accessible. The network limits at point D are for further study.

In deployment case 2, the network limits applicable at reference point D are the same as specified in clause 7.3 for deployment case 1, reference point C.

7.5   Network limit at reference point E

The network limit applicable at reference point E is defined by the specific application as defined in Table 1 of [ITU-T G.8271].

The applications corresponding to classes 4, 5 and 6 according to Table 1 of [ITU-T G.8271] are currently considered in this Recommendation.

Appendix I

Clock models for noise accumulation simulations

(This appendix does not form an integral part of this Recommendation.)

Simulations are needed to define limits on the various noise types described in [ITU-T G.8271]. To perform these simulations, a simulation model that shows how to simulate each noise type it introduces into the timing signal needs to be defined for each network element participating in the time distribution scheme.

I.1 T-BC models for noise accumulation simulations

This clause describes T-BC models for simulating the transport of time using PTP and frequency using synchronous Ethernet and a T-BC model for simulating the transport of both time and frequency using PTP.
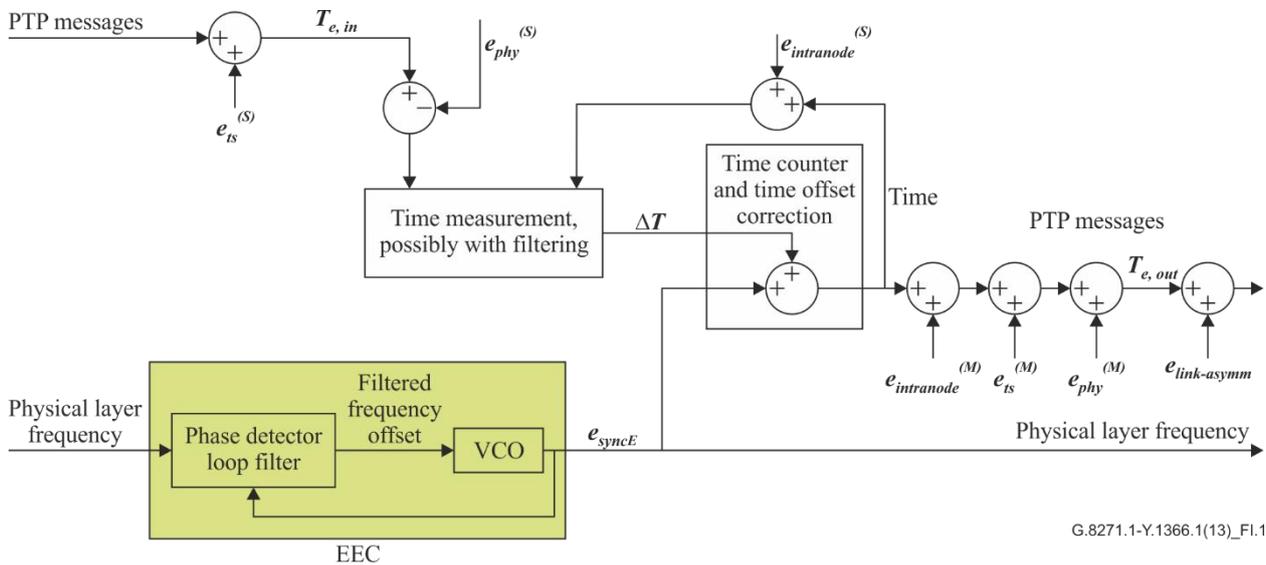
Figure I.1 – Telecom boundary clock model for simulating the transport of time using PTP with synchronous Ethernet assistance

Figure I.1 illustrates a model for simulating the transport of time using PTP with synchronous Ethernet assistance.

NOTE – This model, used for the evaluation of a worst case noise accumulation when synchronous Ethernet is combined with PTP, may not be representative of all possible implementations.

The synchronous Ethernet equipment clock (EEC) block represents an EEC, as specified in [ITU-T G.8262]. The EEC input is a PHY frequency (i.e., a PHY signal that is used as a frequency reference), and its output is a local frequency (i.e., a PHY signal that has a frequency and is local to this node) that is optionally propagated to downstream nodes. The noise process, e_{syncE}, represents the synchronous Ethernet phase noise accumulation in the synchronous Ethernet hypothetical reference model (HRM) (see Appendix II).

The time counter (TC) is incremented by the nominal period of the output clock of the EEC block. For example, if the output clock rate is 125 MHz, then the time counter is incremented by 8 ns each rising edge of the synchronous Ethernet output clock. Upon reception and transmission of PTP event messages, the time counter is sampled. The difference between the actual transmission or reception time and the sampled value of the time counter is modelled as, e_{ts}, since the transmission or reception event can happen between two rising edges of this clock. The effect of e_{ts} on the timestamp for

reception of a PTP event message is shown added at the input, and the effect of e_{ts} on the timestamp for transmission of a PTP event message is shown added at the output.

The incoming PTP messages contain information that may be used to obtain an estimate of the grandmaster (i.e., PRTC) time. This estimate is not perfect; it contains errors introduced by the grandmaster, the upstream nodes, and upstream links. The error in the incoming estimate of the grandmaster time is represented by $T_{e,in}$. The noise process, $e_{phy,}$ represents the effect of asymmetry and timestamp sampling uncertainty on the PHY of the input port. The PHY latency asymmetry may be present if timestamping is done at a point other than the reference plane (i.e., the interface between the PHY and the physical medium). Any latency between the point where timestamping actually is done and the reference plane may be compensated for within PTP. However, any uncompensated latencies that result in asymmetry will contribute to e_{phy}. The noise e_{phy} is subtracted from the timing information contained in the incoming PTP messages due to the direction of the time distribution (note that on the master port of the T-BC it is added). Note that the random process, $e_{phy,}$ may have a static component and a time-varying component.

The timing information contained in the incoming PTP messages, with the noise due to asymmetry on the input port PHY, e_{phy}, and the timestamping error, e_{ts}, is input to the block labelled time measurement, possibly with filtering. This block compares the local time output of the local clock, which is the accumulation of the syncE phase noise, e_{syncE}, and the prior time offset correction, ΔT, with the timing input that represents an estimate of the grandmaster time (with errors as described in the previous paragraph). This block produces the time offset correction, ΔT, between the grandmaster time estimate and the local time. The time measurement block might provide filtering when computing the time offset correction, to reduce the effect of the short-term noise in the observed TE. The filtering characteristics are for further study.

The time counter and time offset correction block produces a local time output (i.e., the output labelled time). The input to the time counter and time offset correction block is the output of the EEC and the time offset correction of the time measurement block. The counter and time offset correction block may include a low-pass filtering function. This has the same effect as increasing the output frequency of the EEC block.

The local time is sampled upon transmission and reception of PTP event messages on master ports. The sampled value is the accumulation of the synchronous Ethernet phase noise, e_{syncE}, the timestamp error, e_{ts}, and the offset correction, ΔT. The error due to asymmetry of the PHY on the output port, e_{phy}, is added to the sampled local time to produce the master port output TE, $T_{e,out}$. The quantity, $T_{e,out}$, is input to the next PTP node (T-BC or T-TSC) downstream via a link model.

Errors due to intranode transmission, $e_{intranode}$, and link asymmetry, $e_{link-asymm}$, must also be included. The former affects both the time correction and the T-BC output. The latter is shown added to the output of the T-BC.

Figure I.2 describes an equivalent model suitable for analytical studies.
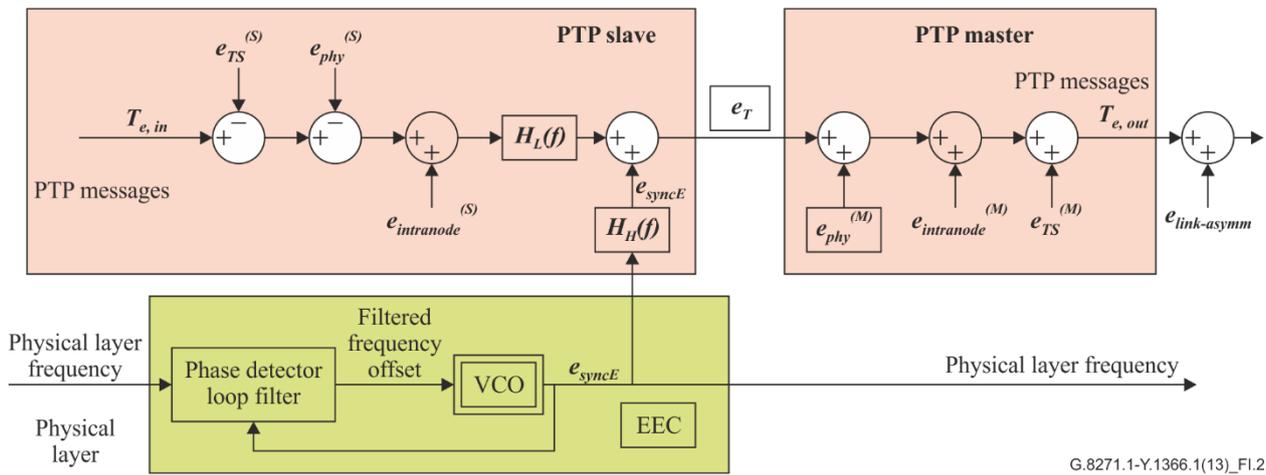
Figure I.2 – Telecom boundary clock model for analytical studies of the transport of time using PTP with synchronous Ethernet assistance

In Figure I.2 the slave clock is assumed to have TE filtering indicated by the low-pass filter $H_L(f)$. The PHY clock noise experiences a high-pass characteristic, $H_H(f)$. When there is no TE filtering, the PHY clock introduces a TE corresponding to the wander (e_{syncE}) that occurs between successive estimates of the time offset correction.

Figure I.3 depicts a model using PTP for time and frequency. The details for this model are for further study.
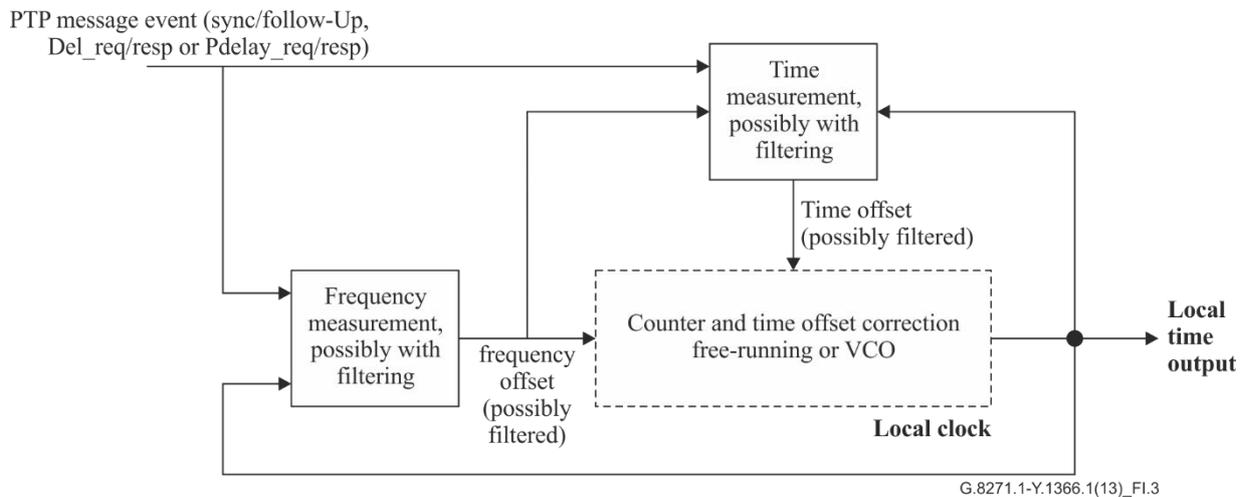
NOTE – The ingress and egress hardware timestamping needs to be modelled and taken into account.

Figure I.3 – Telecom boundary clock model using PTP for time and frequency

In Figure I.3, note the following.

– PTP messages are used for both frequency and time measurements. The PTP messages are timestamps based on the local time output.

– The frequency measurement block uses PTP messages to make frequency measurements. For frequency measurements there are several possibilities (e.g., Sync or Pdelay_req messages) and these are for further study. The frequency measurements could involve filtering and is for further study. The PTP messages are timestamps based on the local time output.

– The time measurement block uses PTP messages for computing a time offset; this block should consider sources of errors such as the effect of timestamping. The PTP messages are timestamps based on the local time output. The time measurement block might provide

filtering, for example, to reduce the effect of the error produced by the timestamping function. The filtering characteristics are for further study.

– The local clock block includes a counter to produce a local timebase output. The input into this block is a frequency measurement from the frequency measurement block and a time correction from the time measurement block. The ways in which these are used is for further study.

For the simulation model using PTP for time and frequency, it can be assumed that filtering is implemented in each boundary clock with a phase-locked loop (PLL)-based clock.

I.2 End-to-end TC models for noise accumulation simulations

This clause describes models for simulating the noise added by a PTP transparent clock when using synchronous Ethernet or a free running local oscillator (see [IEEE 1588-2008] for details on the transparent clock functions). The models for the case where PTP is the source for frequency reference are for further study.

Figure I.4 illustrates a model for simulating the transport of time using PTP with optional synchronous Ethernet assistance for the case of an end-to-end transparent clock.

NOTE 1 – This model, used for the evaluation of a worst case noise accumulation when synchronous Ethernet is combined with PTP, may not be representative of all possible implementations.

NOTE 2 – This model accounts for the noise added by the end-to-end transparent clock to the PTP flow in one direction only. End-to-end transparent clocks operate independently of the PTP traffic flow direction.
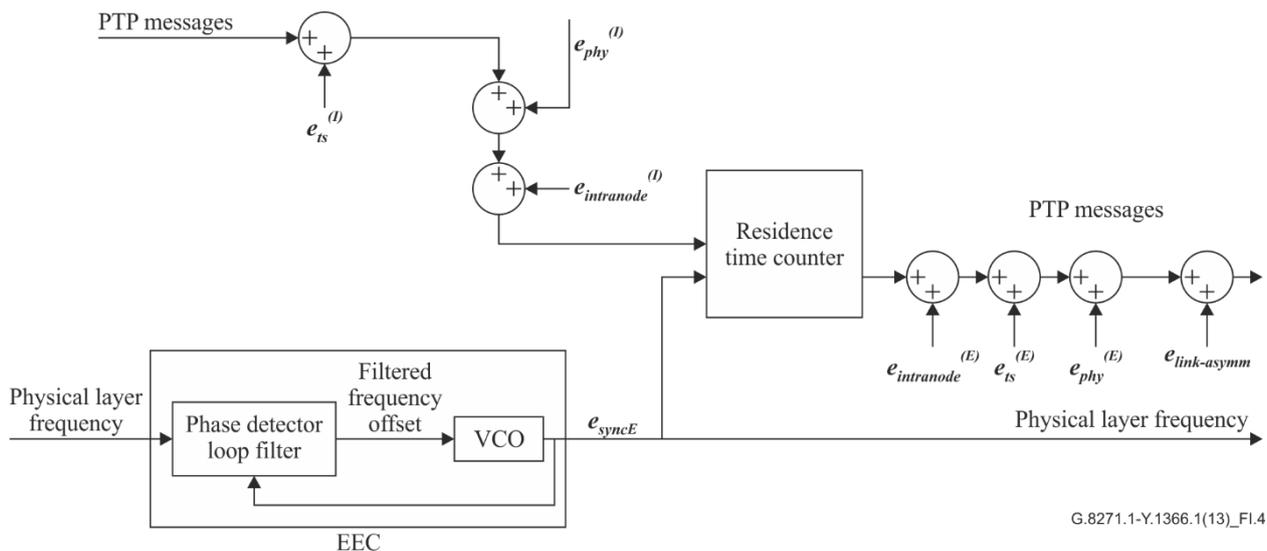

Figure I.4 – Telecom end-to-end transparent clock model for simulating the transport of time using PTP with synchronous Ethernet assistance

The EEC block represents an EEC as specified in [ITU-T G.8262]. The EEC input is a PHY frequency (i.e., a PHY layer signal that is used as a frequency reference), and its output is a local frequency (i.e., a PHY layer signal that has a frequency and is local to this node) that is optionally propagated to downstream nodes. The noise process, e_{syncE}, represents the synchronous Ethernet phase noise accumulation in the synchronous Ethernet HRM (see Appendix II).

The residence time counter is incremented by the nominal period of the output clock of the EEC block. For example, if the output clock rate is 125 MHz, then the residence time counter is incremented by 8 ns each rising edge of the synchronous Ethernet output clock. Upon reception and transmission of PTP event messages, the residence time counter is sampled. The difference between the actual transmission or reception time and the sampled value of the time counter is modelled as e_{ts},

since the transmission or reception event can happen between two rising edges of this clock. The effect of e_{ts} on the timestamp for reception of a PTP event message is added at the input, and the effect of e_{ts} on the timestamp for transmission of a PTP event message is added at the output. Note that e_{ts} for ingress and egress ports can be uncorrelated and can be of different polarity.

The noise process, e_{phy}, represents the effect of asymmetry and timestamp sampling uncertainty on the PHY. The PHY latency asymmetry may be present if timestamping is done at a point other than the reference plane (i.e., the interface between the PHY and the physical medium). Any latency between the point where timestamping actually is done and the reference plane may be compensated for within PTP. However, any uncompensated latencies that result in asymmetry will contribute to e_{phy}. The noise, e_{phy}, is added to the timing information contained in the incoming PTP messages. Note that the random process, e_{phy}, may have a static component and a time-varying component.

The residence time counter produces a residence time. The input to the residence time counter is the frequency output of the EEC and the ingress and egress time for the PTP event frame.

The residence time counter is sampled upon reception of PTP event messages on ports. The residence time counter will add the accumulation of the synchronous Ethernet phase noise, e_{syncE}, during the residence time.

Errors due to intranode transmission, $e_{intranode}$, and link asymmetry, $e_{link-asymm}$, must also be included. The latter is shown added to the output of the TC.

Figure I.5 is an equivalent model suitable for analytical studies.
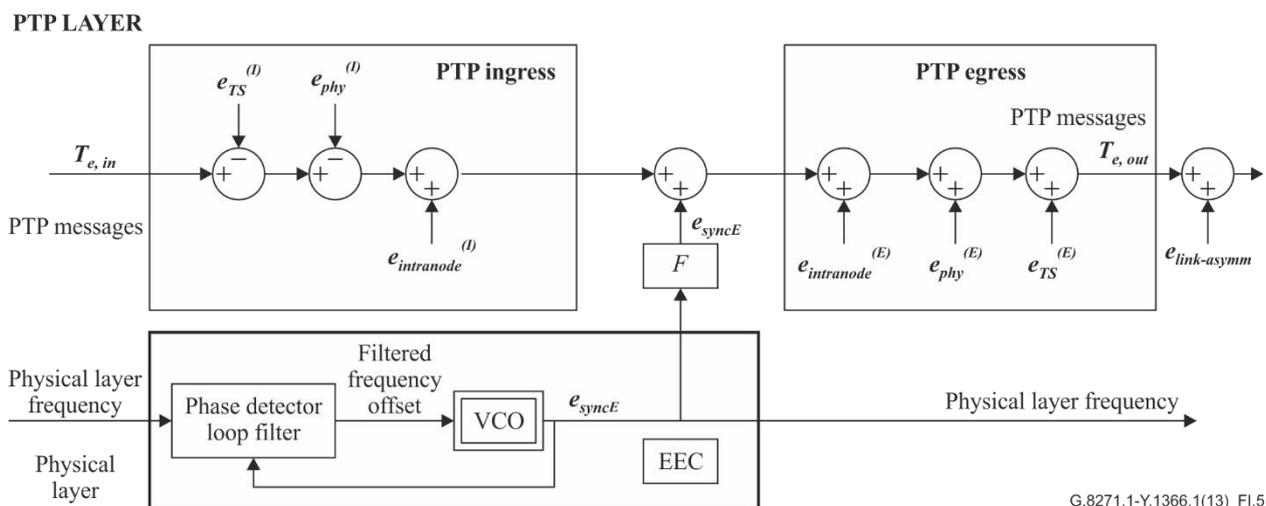
Figure I.5 – Telecom transparent clock model for analytical studies of the transport of time using PTP with synchronous Ethernet assistance.

In Figure I.5, the PHY clock introduces a TE corresponding to the wander (e_{syncE}) that occurs between the ingress timestamp point and the egress timestamp point. This is equivalent to the time interval error over an observation interval equal to the packet's residence time. As a conservative approximation, this can be modelled as the change of the local clock's TE signal over the maximum allowed residence time R. In Figure I.5 this is indicated by the operator F.

The value of the maximum residence time, R, is for further study. The model for a TC using a free running oscillator to measure the residence time can be modelled using the same model with the EEC replaced with a model for a free running oscillator. This is shown in Figure I.6. For free-running oscillators that have a significant frequency offset, or for relatively large residence times, the error introduced may be dominated by this frequency offset.
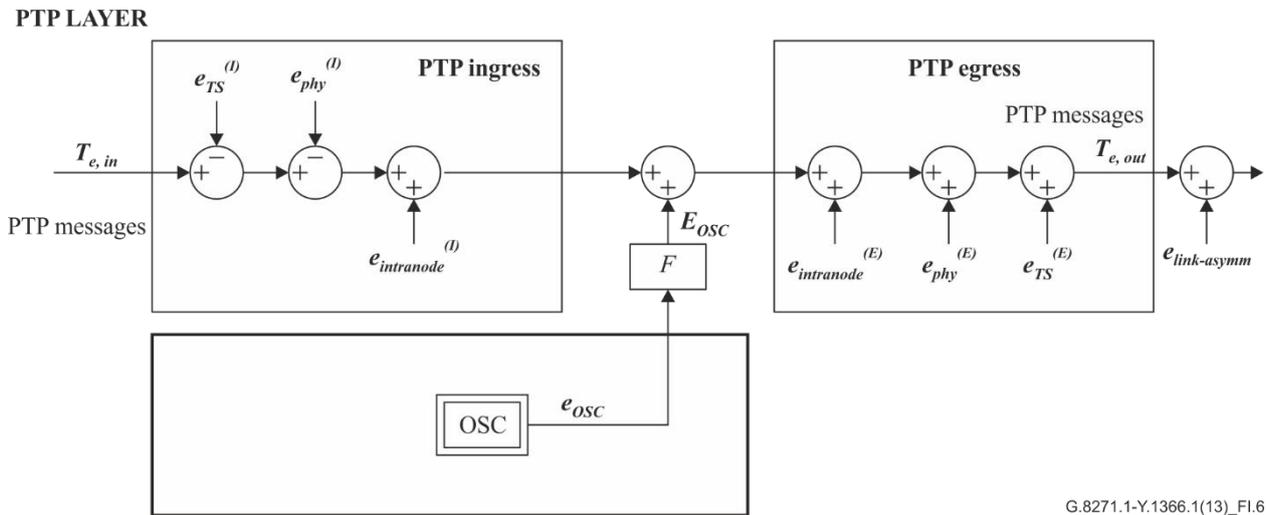
Figure I.6 – Telecom transparent clock model for analytical studies of the transport of time using PTP without synchronous Ethernet assistance

The simulation model for an end-to-end transparent clock using PTP for frequency reference (syntonized transparent clock) is for further study.

Appendix II

Hypothetical reference models used to derive the network limits

(This appendix does not form an integral part of this Recommendation.)

II.1   HRM composed of T-BCs

The HRM models that are presented in clauses II.1.1 to II.1.3 are applicable to the network reference models defined in Figure 4 of [ITU-T G.8271] and Figure 7-1. This is essential to derive the network limits between points B and C when the packet network consists of network elements with T-BCs.

The purpose of these HRMs is to:

–   establish reasonable worst case network models for phase or time distribution using T-BCs;

–   derive network limits and verify that they are consistent with performance requirements – some of the performance requirements are summarized in Table 1 of [ITU-T G.8271];

–   construct end-to-end phase and TE budget.

To determine the network limits, the most important aspects that need to be considered when a reference network is constructed are those that influence the accumulation of phase and TE of a reference packet time signal that is transported, and some of these are as follows.

–   Specification of individual clocks and their noise specifications. In this case, [ITU-T G.8273] shall be considered for the characteristics of the clock implemented in the T-BC. The model of the T-BC for noise accumulation simulations is described in Appendix I.

–   The composition of a synchronization chain, cascade of clocks and ordering of clocks. This is defined by the related HRM.

–   Other sources of errors besides the noise generated by clocks. These are described in Appendix I of [ITU-T G.8271].

The following HRMs are based on a shorter chain of 12 clocks and a longer chain of 22 clocks.

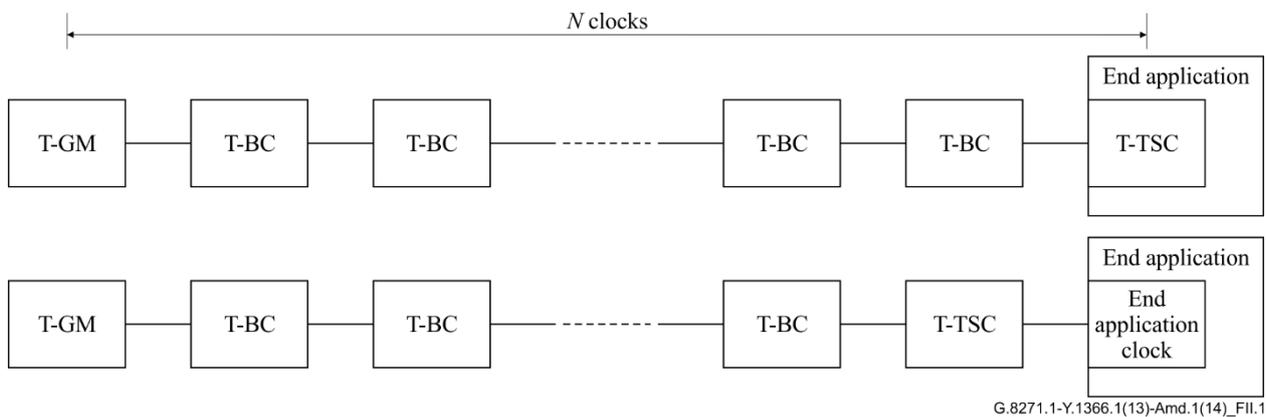## II.1.1   HRM without physical layer frequency support from the network

The reference chain in this clause shows a T-GM clock and a T-TSC interconnected by a number of T-BCs.

In this HRM-1 model, both frequency and time are transported via PTP. Both frequency and time follow the same synchronization path. The T-GM acts as both the source of frequency and time (e.g., the T-GM can receive its time and frequency from a global navigation satellite system (GNSS) receiver).

At the end of the chain, the phase/time reference is delivered to an end application (e.g., a mobile base station). Two cases are possible and are represented in Figure II.1:

1)   the T-TSC is embedded in the end application;

2)   the T-TSC is external to the end application, and delivers the phase/time reference to the end application via a phase/time synchronization distribution interface (e.g., a 1 PPS interface).

NOTE 1 – A specific equipment implementation may also be based on implementing a T-BC function (instead of a T-TSC function) and delivering the phase/time reference to the end application via a phase/time synchronization distribution interface.

Figure II.1 – HRM-1 without physical layer frequency support

The number of clocks, *N*, cascaded in the HRM-1 for the shorter chain is 12. It corresponds to:

– one T-GM, 10 T-BCs and one T-TSC for the case of a T-TSC embedded in the end application;

– one T-GM, nine T-BCs, one T-TSC and the end application clock for the case of a T-TSC external to the end application.

The number of clocks, *N*, cascaded in the HRM-1 for the longer chain is 22. It corresponds to:

– one T-GM, 20 T-BCs and one T-TSC for the case of a T-TSC embedded in the end application;

– one T-GM, 19 T-BCs, one T-TSC and the end application clock for the case of a T-TSC external to the end application.

NOTE 2 – Noise accumulation in networks without PHY frequency synchronization support is for further study.

The PHY connection between two T-BCs may not necessarily be Ethernet. For example, some T-BCs may be linked using microwave, xDSL, xPON or OTN technology. Such devices are called media converters.

Figure II.2 shows a variation of the HRM where some unnamed technology is used to connect two of the T-BCs, or the T-BC and the T-TSC. The clock specification for the T-BC should be independent of the PHY medium used for the connection.
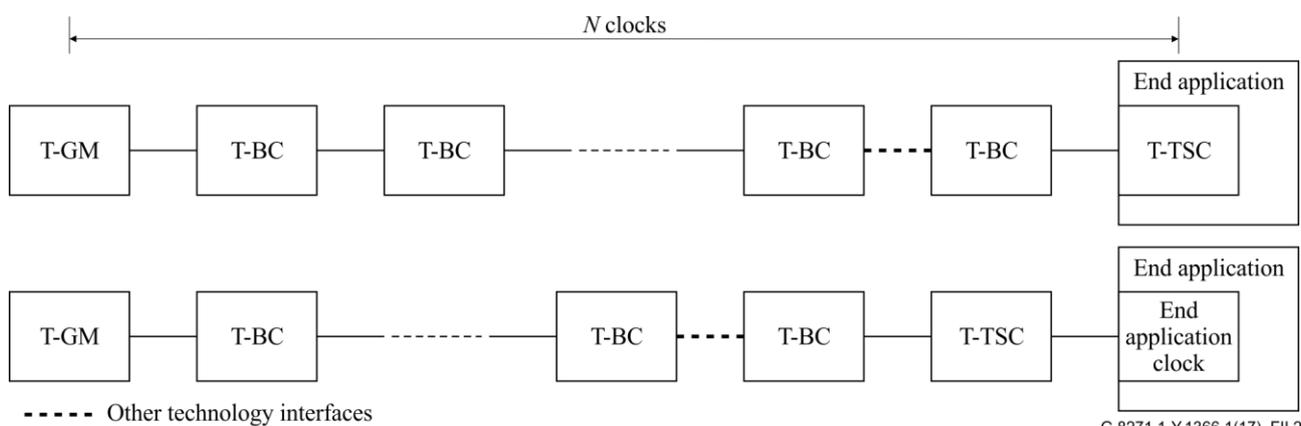
Figure II.2 – HRM-1, including some links using other technology interfaces

Where media converters are used in the network, the number *N* is for further study.

II.1.2 HRM with physical layer frequency support from the network

The reference chains in this clause represent the cases where phase/time is transported via PTP and frequency via synchronous digital hierarchy (SDH)/synchronous Ethernet.

NOTE 1 – The analysis has been done with a synchronous Ethernet network based on option 1 EECs (see [ITU-T G.8262]).

Congruent scenario

In this HRM-2 model, both frequency and phase/time follow the same synchronization path.

At the end of the chain, the phase/time reference is delivered to an end application (e.g., a mobile base station). Two cases are possible and are represented in Figure II.3.

1)   The T-TSC is embedded in the end application.

2)   The T-TSC is external to the end application, and delivers the phase/time reference to the end application via a phase/time synchronization distribution interface (e.g., 1 PPS interface).

NOTE 2 – A specific equipment implementation may also be based on implementing a T-BC function (instead of a T-TSC function) and delivering the phase/time reference to the end application via a phase/time synchronization distribution interface.
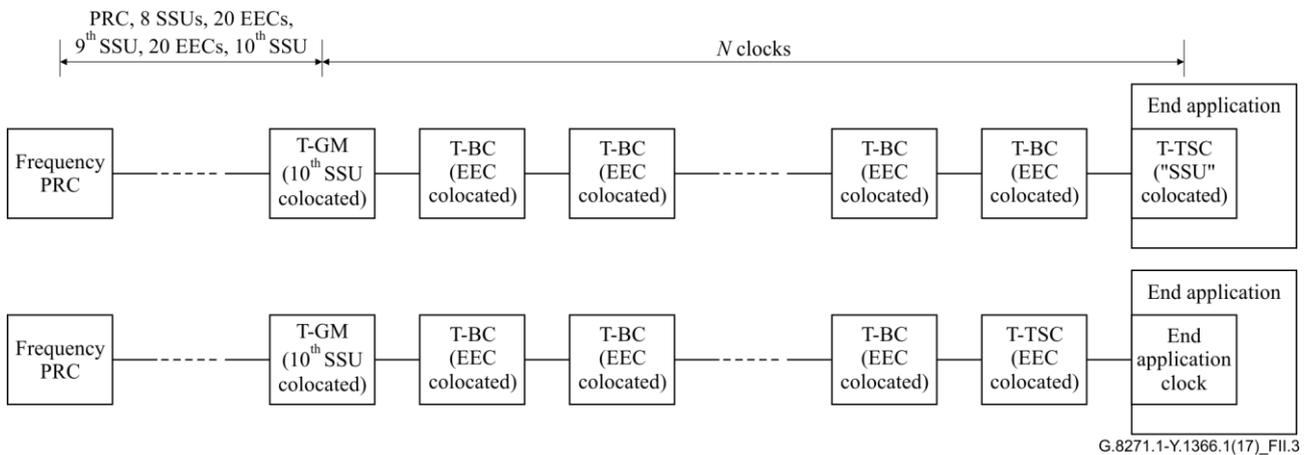

Figure II.3 – HRM-2 with physical layer frequency support – congruent scenario

The number of clocks, N, cascaded in the HRM-2 for the shorter chain is 12. It corresponds to:

–   one T-GM, 10 T-BCs and one T-TSC for the case of a T-TSC embedded in the end application;

–   one T-GM, nine T-BCs, one T-TSC and the end application clock for the case of a T-TSC external to the end application.

The number of clocks, N, cascaded in the HRM-2 for the longer chain is 22. It corresponds to:

–   one T-GM, 20 T-BCs and one T-TSC for the case of a T-TSC embedded in the end application;

–   one T-GM, 19 T-BCs, one T-TSC and the end application clock for the case of a T-TSC external to the end application.

The following PHY frequency clocks are co-located with the PTP clocks:

–   for the T-GM: a synchronization supply unit (SSU) supporting phase/time transport;

–   for the T-BC: an EEC supporting phase/time transport;

–   for the T-TSC external to the end application: an EEC supporting phase/time transport;

–   for the T-TSC embedded in the end application: the clock supporting phase/time transport is for further study. The initial assumption is that this clock might be close to the characteristics of an SSU (e.g., equivalent type of oscillator, but some characteristics of the clock may be different, e.g., different bandwidth). For the purpose of the simulations, it is assumed that this clock is the only timing function of the end application (no other clock is cascaded after).

The SDH/synchronous Ethernet reference chain is a full ITU-T G.803 reference chain with the EECs as close to the end of the chain as possible: a PRC, followed by 8 SSUs, followed by 20 EECs, followed by an SSU, followed by 20 EECs, followed by an SSU (co-located with the T-GM), followed by 9 EECs (each co-located with a T-BC) related to the shorter chain or 19 EECs (each co-located with a T-BC) related to the longer chain, followed by a final EEC (co-located with the T-TSC external to the end application or with a last T-BC). A final clock is at the end of the chain: either the "end application clock", or a clock co-located with the T-TSC embedded in the end application.
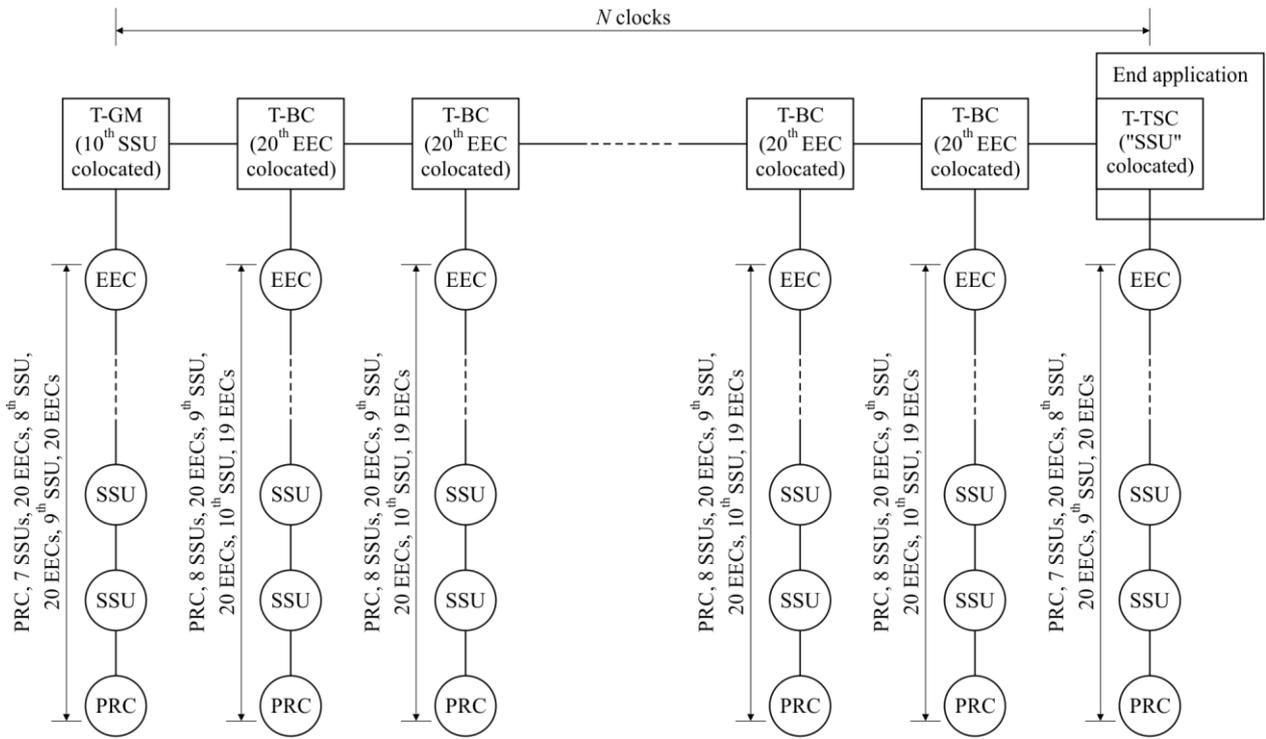
Non-congruent scenario

In this HRM-3 model, phase/time and frequency synchronization follow different synchronization paths (i.e., phase/time is distributed horizontally and frequency vertically). This model is similar in spirit to Figure A.1 of [ITU-T G.823] and is used to represent a possible worst case scenario when PTP and SDH/synchronous Ethernet are used.

At the end of the chain, the phase/time reference is delivered to an end application (e.g., a mobile base station). Two cases are possible and are represented in Figures II.4 and II.5:

1)   the T-TSC is embedded in the end application;

2)   the T-TSC is external to the end application, and delivers the phase/time reference to the end application via a phase/time synchronization distribution interface (e.g., 1 PPS interface).

NOTE 3 – A specific equipment implementation may also be based on implementing a T-BC function (instead of a T-TSC function) and delivering the phase/time reference to the end application via a phase/time synchronization distribution interface.

**Figure II.4 – HRM-3 with physical layer frequency support –
non-congruent scenario, deployment case 1**
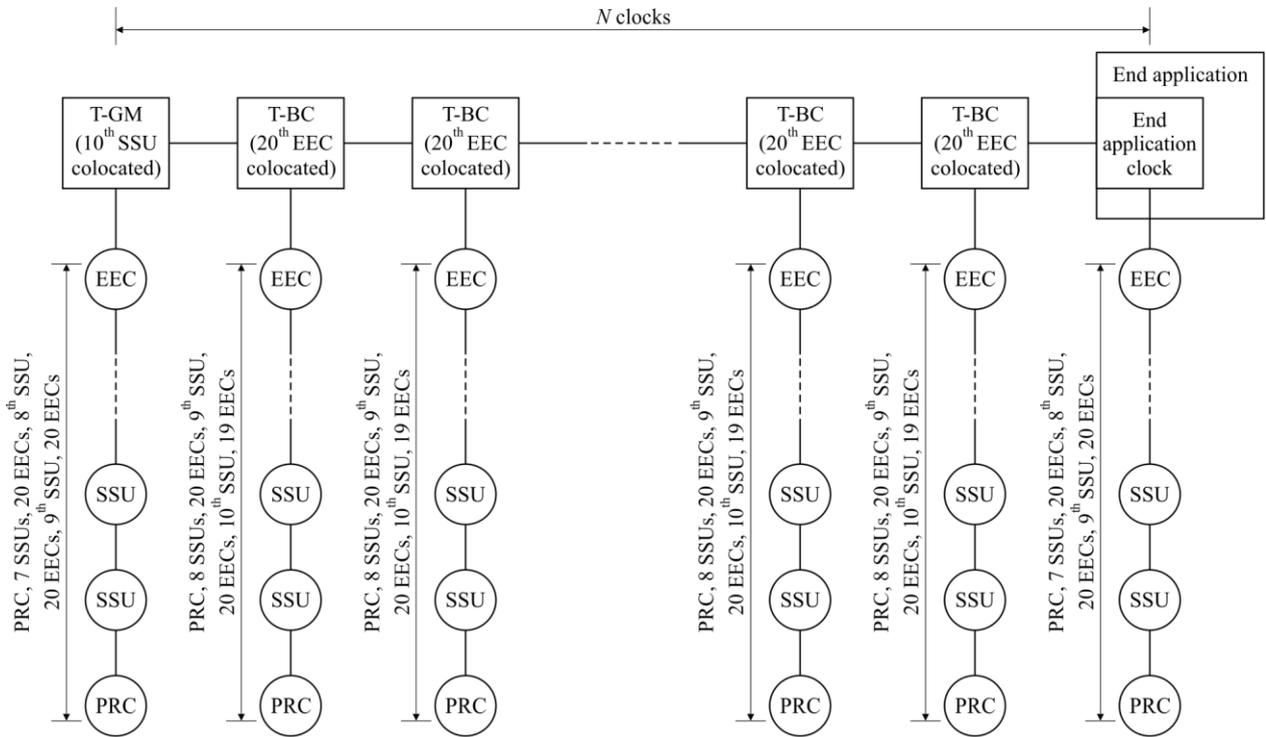
**Figure II.5 – HRM-3 with physical layer frequency support –
non-congruent scenario, deployment case 2**

The number of clocks, N, cascaded in the HRM-3 for the shorter chain is 12. It corresponds to:

– one T-GM, 10 T-BCs and one T-TSC for the case of a T-TSC embedded in the end application;

– one T-GM, nine T-BCs, one T-TSC and the end application clock for the case of a T-TSC external to the end application.

The number of clocks, N, cascaded in the HRM-3 for the longer chain is 22. It corresponds to:

– one T-GM, 20 T-BCs and one T-TSC for the case of a T-TSC embedded in the end application;

– one T-GM, 19 T-BCs, one T-TSC and the end application clock for the case of a T-TSC external to the end application.

The following PHY frequency clocks are co-located with the PTP clocks as follows.

– For the T-GM: an SSU supporting phase/time transport.

– For the T-BC: an EEC supporting phase/time transport.

– For the T-TSC external to the end application: an EEC supporting phase/time transport.

– For the T-TSC embedded in the end application: the clock supporting phase/time transport is for further study. The initial assumption is that this clock might be close to the characteristics of an SSU (e.g., equivalent type of oscillator, but some characteristics of the clock may be different, e.g., different bandwidth). For the purpose of the simulations, it is assumed that this clock is the only timing function of the end application (no other clock is cascaded after).

The SDH/synchronous Ethernet reference chain is a full ITU-T G.803 reference chain with the EECs as close to the end of the chain as possible (the final SSU may be at the end of the chain):

– for the PTP clocks supported by an EEC: a PRC, followed by 8 SSUs, followed by 20 EECs, followed by an SSU, followed by 20 EECs, followed by an SSU, followed by 19 EECs with the 20th EEC being integrated into the T-BC or T-TSC clock;

– for the PTP clocks supported by an SSU: a PRC, followed by 7 SSUs, followed by 20 EECs, followed by an SSU, followed by 20 EECs, followed by an SSU, followed by 20 EECs with the 10th SSU being integrated into the T-GM or T-TSC clock.

II.1.3   HRM for cluster-based synchronization

The reference chain in this clause shows a T-GM clock and a T-TSC interconnected by a number of T-BCs. The reference chains are based on a longer chain of N clocks between the T-GM and T-TSC representing the joint part of the synchronization supply chain, which is common for all base stations and a shorter chain of M clocks between the part of the synchronization supply chain that is used for the specific base station only (which is part of the base station cooperation cluster). The number of clocks N cascaded in the longer chain and the number of clocks M cascaded in the shorter chain are independent of each other. See Figures II.6 and II.7.
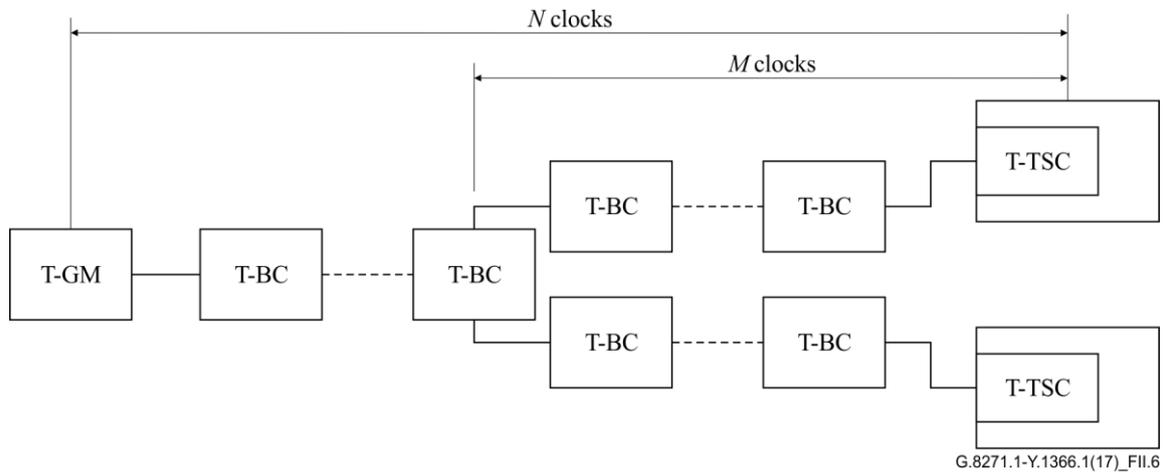
Figure II.6 – HRM-4 for cluster based synchronization without physical layer frequency support
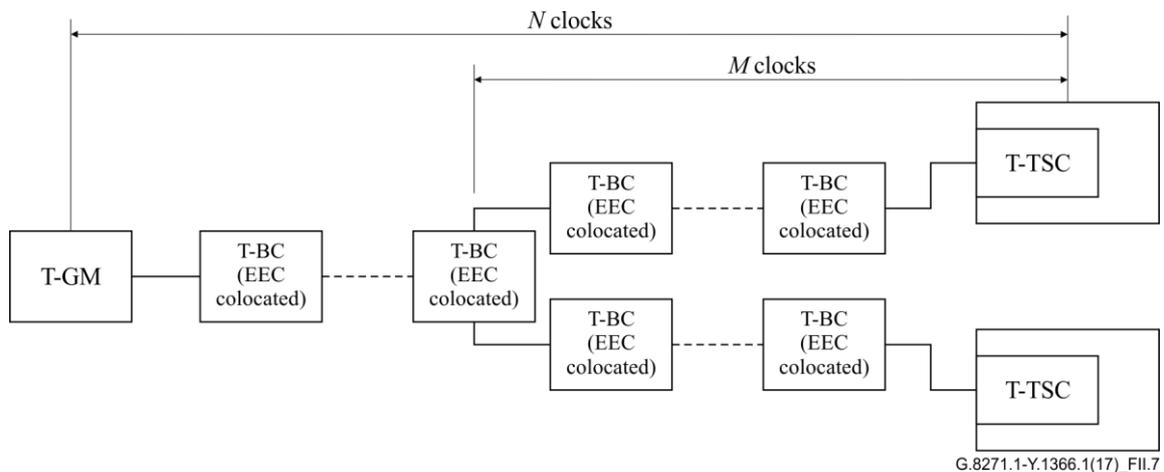
Figure II.7 – HRM-4 for cluster based synchronization with physical layer frequency support

The number of clocks, *N* and *M*, are for further study.

The number of clocks, *M*, cascaded in the shorter chain in the HRM depends upon the specific application as per Table 2 of [ITU-T G.8271].

II.2 HRM composed of T-BCs and T-TCs

II.2.1 HRM with physical layer frequency support from the network

For the case of HRM with PHY frequency support from the network, the same models as described in Figure II.3 and Figure II.4 apply where a maximum number of eight T-TCs are included in the reference chain. Note that it is typical for T-TCs to be deployed close to the end application. The T-TCs may be followed by T-BCs.

Appendix III

Network limits considerations

(This appendix does not form an integral part of this Recommendation.)

III.1 Measurement of network limits in deployment case 1

If a network has full timing support and a T-BC as the last piece of equipment in the chain, the measurement of the network limits for deployment case 1 at reference point C can be performed according to the following main approaches (note, a T-TC may be integrated into the chain; this is for further study):
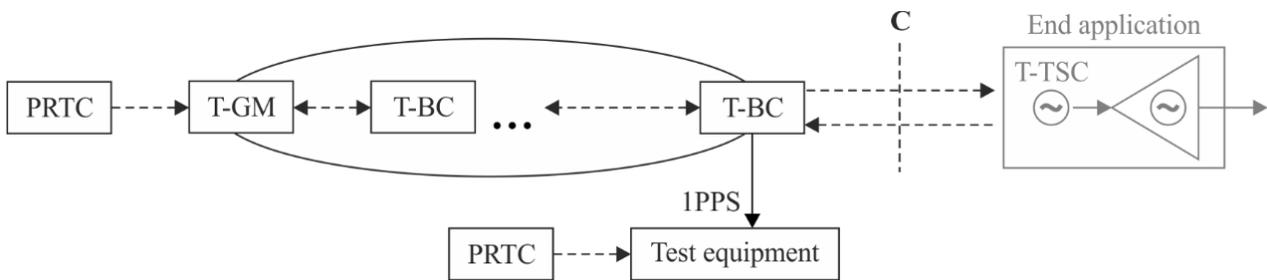
a)   If available, via the output PPS test interface from the last BC of the chain (see Figure III.1). Note that, any additional source of error between the 1 PPS measurement point and the actual reference point C has to be taken into account (e.g., link asymmetry).

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Figure III.1 – Deployment case 1 of network limits measurement, option a)

b)   Directly from the two-way PTP flow via passive PTP monitor equipment (see the packet timing monitor definition in clause 3.1.14 of [ITU-T G.8260]) connected to the test equipment. With the passive technique, a packet-based test device monitors packet exchanges over a communication link. In this way, the test device acts as an observer and it does not directly participate in the packet timing protocol, and there may be significant other non-synchronization-related traffic loading the T-BC port in addition to the synchronization packets of interest. This measurement can be performed by monitoring the outgoing Sync messages (and Follow_Up messages in case of two-steps clocks). Compensation for the additional delay between the T-BC output port and the test equipment is required. In particular, if the cable delay from the master port to the tap is known as X ns and the monitor establishes the time-of-passage of the Sync message at the tap as TM2 and extracts the time-of-departure from the master port as the time-stamp T1 (it may need to use the Follow_up), the forward TE of the master port is estimated as:

$$T_{\text{fwd\_error}} \approx (\text{TM2} - \text{T1} - X) \tag{III-1}$$

As an alternative, the packets in the reverse direction could also be used. In this case, the Delay_Request messages can be timestamped by the PTP monitor with corresponding Delay_Response messages providing timestamps from the T-BC. As before, compensation for the additional delay between the T-BC output port and the test equipment is required. For a cable delay of X ns, if the PTP Monitor timestamp of the Delay_Request message is TM3 and the timestamp from the Delay_Response message is T4, the reverse TE of the master port is estimated as the reverse time-stamp error:

$$T_{\text{rev\_error}} \approx (\text{TM3} - \text{T4} + X) \tag{III-2}$$

According to a further alternative approach, the measurement can be performed using the full set of PTP messages exchanged between the T-TSC and the T-BC. In particular, the monitor establishes the time-of-passage of the Sync message at the tap as TM2 and reads the

time-of-departure of the Sync message from the master port as T1. It also establishes the time-of-passage of the Delay_Request message at the tap as TM3 and reads the time-of-arrival of the Delay_Request message at the master port from the Delay_Response message as T4. Assuming that the packet rates in the two directions are the same and that the Sync message and Delay_Request message are close together in time, combined forward and reverse TE, or time-transfer error, at the (master) port of the T-BC can be estimated as:

$$T_{combined\_error} \approx (TM2 - T1 - T4 + TM3)/2 \qquad (III-3)$$

The case where the forward and reverse packet rates are different, or require interpolation, is for further study.

The effective TE of the T-BC, $T_{err}(t)$ (either the forward time-stamp error, reverse time-stamp error or combined error) may be used to estimate the relevant metrics, such as the constant TE as described in [ITU-T G.8260].

Note that, because this Recommendation addresses network performance requirements, it is expected that Formulae (III-1) to (III-3) provide equally valid estimates of the TE of the T-BC internal clock.

Additional information regarding measurement of master port time-stamp error and time-transfer error is available in Annex A of [ITU-T G.8273].
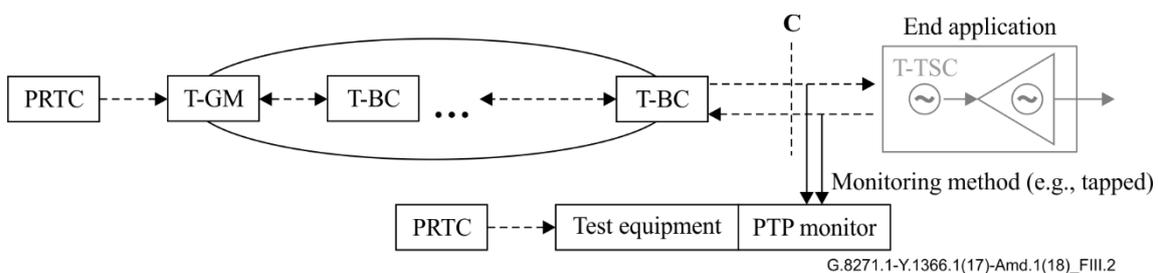
This approach is depicted in Figure III.2.

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Figure III.2 – Deployment case 1 network limits measurement, option b)

c)   From the two-way PTP flow via an active measurement probe (e.g., prior to the start of the service or connecting the active monitor to a dedicated port of the T-BC). The measurement is performed using the full set of the PTP messages exchanged between the test equipment and the T-BC.

In particular, the monitor establishes the time-of-arrival of the Sync message as T2 and reads the time-of-departure of the Sync message from the master port as T1. It also establishes the time-of-departure of the Delay_Request message from the PTP Monitor as T3 and reads the time-of-arrival of the Delay_Request message at the master port from the Delay_Response message as T4. Assuming that the Sync message and Delay_Request message packet rates are the same and that the Sync message and Delay_Request message are close together in time, an estimate of the TE at the port of the T-BC can be computed as:

$$T_{combined\_error} \approx (T2 - T1 - T4 + T3)/2$$

The case where the forward and reverse packet rates are different or require interpolation is for further study.

Additional information regarding measurement of the master port time-stamp error and time-transfer error is provided in Annex A of [ITU-T G.8273].

Assuming all ports of the T-BC behave similarly, the effective TE of the T-BC, $T_{err}(t)$ (either the forward time-stamp error, reverse time-stamp error or combined error) may be used to estimate the relevant metrics, such as the constant TE as described in [ITU-T G.8260].

This approach is described in Figure III.3.

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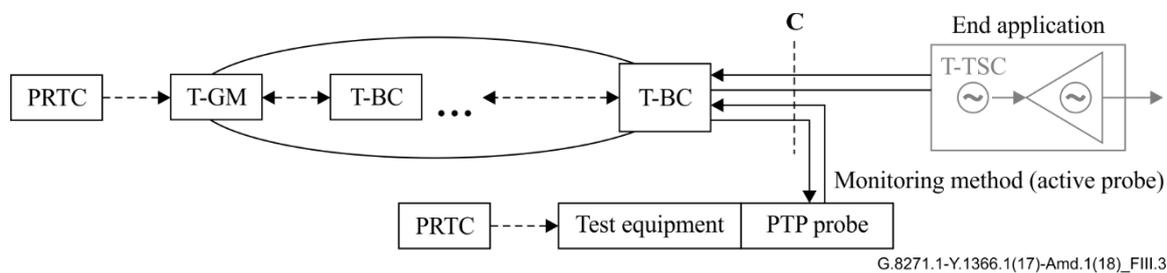
Figure III.3 – Deployment case 1 network limits measurement, option c)

In all cases the measurement is performed with respect to a PRTC. When the PRTC used for the PTP probe is independent of the PRTC used for the network, then the influence of the time error of the independent PRTCs should be taken into account when analyzing the test results against the network performance limits.

In all cases, the measurement is performed with respect to a PRTC.

Appendix IV

Constant and dynamic time error and error accumulation

(This appendix does not form an integral part of this Recommendation.)

IV.1   Introduction

Network limits for TE are expressed in terms of maximum absolute TE. That is, if TE measurement data is the sequence, $\{x(n\tau_0)\}$, the maximum absolute TE is

$$\max|TE| = \max_n |x(n\tau_0)| \tag{IV-1}$$

It may be advantageous to consider the TE in terms of "time-wander" and "time-jitter", representing the lower and higher frequency components of the TE. Denoting the low-pass-filtered version of $\{x(n\tau_0)\}$ by $\{y(n\tau_0)\}$, the maximum absolute time-wander is given by

$$\max|TE_W| = \max_n |y(n\tau_0)| \tag{IV-2}$$

where the subscript W indicates that the measurement is related to time-wander. The Fourier frequency separating time-wander (the cut-off frequency of the low-pass filter) is for further study.

The TE measurement data, $\{x(n\tau_0)\}$, is generated either from the packet-based timing signal (e.g., PTP) or from a dedicated time output signal (e.g., 1 PPS).

IV.2   Components of time error

The accumulated TE, $TE(t)$, at any reference point may be expressed in terms of a constant and a dynamic TE component, indicated as cTE and $dTE(t)$, respectively.

$$TE(t) = cTE + dTE(t) \tag{IV-3}$$

Constant TE, defined in [ITU-T G.8260], is a useful construct to express TE components that are immune to filtering. Such TE components are the result of, for example, asymmetry in the transmission medium between network elements, asymmetries within network elements, the beating effect in near-synchronous time-stamping, and so on. The power-spectrum of the constant TE is assumed to be equivalent to a delta function at $f = 0$ in the Fourier frequency domain.

The dynamic TE component, $dTE(t)$, is related to random noise accumulation (e.g., due to T-BC time-stamping or wander accumulated in the synchronous Ethernet network and injected into the time synchronization plane when synchronous Ethernet is used in combination with PTP or due to packet-delay variation experienced by the timing signal packets). The power spectrum of the dynamic TE is spread out over the Fourier frequency domain and the power can be reduced, to some extent, by low-pass filtering (e.g., as a result of the bandwidth of a given clock function within a network element).

To facilitate the analysis, it helps to further decompose the dynamic TE signal into two uncorrelated subcomponents: $d^H TE(t)$ and $d^L TE(t)$ which represent the high and low frequency sub-bands of the dynamic TE, and where the bands are divided based on the bandwidth of the filter action of network element, i. Such decomposition is useful for analysing the accumulation of noise in a chain of time clocks. (Analysis of transient and hold-over budgets is also important, but is separate from this discussion.) To a first approximation, the low-pass filter action of the network element can be modelled as an ideal low-pass filter with cut-off frequency B (Hz),

$$dTE(t) = d^L TE(t) + d^H TE(t) \tag{IV-4}$$

which separates the total TE into three components:

$$TE(t) = cTE + d^L TE(t) + d^H TE(t) \tag{IV-5}$$

The above decomposition of TE into three sub components is illustrated in Table IV.1.

Table IV.1 – Decomposition of time error into sub-components

$TE(t)$	cTE	
	$dTE(t)$	$d^{\mathrm{H}}TE(t)$
		$d^{\mathrm{L}}TE(t)$

IV.3 Accumulation of time error in a chain of clocks

The accumulation of TE in a chain of clocks can be analysed in terms of the constant time error and dynamic TE components introduced above. It is important to note that the three components of TE described above accumulate differently. Specifically, the inherent low-pass nature of the clock filtering in a network element affects the incoming dynamic TE but passes the incoming constant TE component essentially unchanged. Furthermore, the network element may add both constant and dynamic TE. One approach to illustrating the accumulation of TE is described with reference to Figure IV.1.
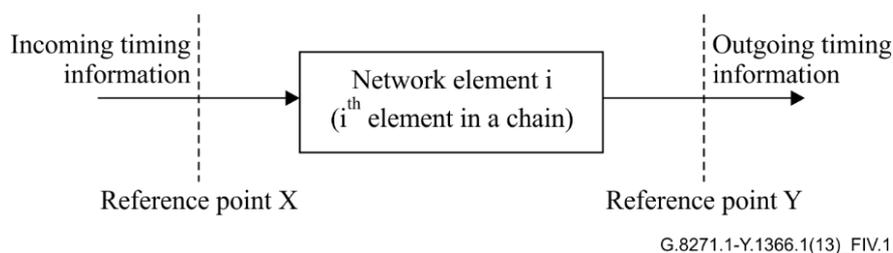

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Figure IV.1 – Accumulation of time error

The maximum absolute TE at reference points X and Y are:

$$\max|TE_{\mathrm{X}}(t)| = \max|cTE_{\mathrm{X}} + dTE_{\mathrm{X}}(t)| \tag{IV-6}$$

$$\max|TE_{\mathrm{Y}}(t)| = \max|cTE_{\mathrm{Y}} + dTE_{\mathrm{Y}}(t)| \tag{IV-7}$$

where the subscripts X and Y indicate the value measured at reference points X and Y, respectively.

The constant TE at Y can be represented as the sum of the constant TE at X (cTE_{X}) plus the constant TE generated internally by the network element i (cTE_i):

$$cTE_{\mathrm{Y}} = cTE_{\mathrm{X}} + cTE_i \tag{IV-8}$$

The dynamic TE, dTE_{Y}, at Y is more complex, because a simple sum cannot be used. This is because the network element introduces a low-pass filter. As described above, the dynamic TE at X (the input of the network element i) can be decomposed into high and low band sub-components:

$$dTE_{\mathrm{X}}(t) = d^{\mathrm{L}}TE_{\mathrm{X}}(t) + d^{\mathrm{H}}TE_{\mathrm{X}}(t) \tag{IV-9}$$

and the dynamic TE introduced by the network element i can similarly be expressed in terms of low-frequency and high-frequency components as:

$$dTE_i(t) = d^{\mathrm{L}}TE_i(t) + d^{\mathrm{H}}TE_i(t) \tag{IV-10}$$

Then, the dynamic TE at Y (the output of the network element i), is a combination of the dynamic TE introduced by element i and the dynamic TE at X, the input dynamic TE being filtered by the processing of that element. The high band dynamic TE at X will, to a first approximation, be filtered out by the network element, while the low band dynamic TE at X will, to a first approximation, be passed through the network element. Low-band dynamic TE generated by the network element will, to some extent, be compensated by the time-tracking action of the network element, but some residual low-band dynamic TE is expected to remain.

Therefore, we can represent the dynamic TE at Y in terms of the low band dynamic TE at X $[d^L TE_X(t)]$, and the dynamic TE generated internally by network element i $[d^L TE_i(t)$ and $d^H TE_i(t)]$:

$$dTE_Y(t) \cong d^L TE_X(t) + d^L TE_i(t) + d^H TE_i(t) \qquad \text{(IV-11)}$$

Substituting these two decompositions into the equation for maximum absolute TE at Y, we get the following expression:

$$\max|TE_Y| = \max|(cTE_X + cTE_i) + (d^L TE_X(t) + d^L TE_i(t)) + d^H TE_i(t)| \qquad \text{(IV-12)}$$

Therefore, the maximum absolute TE at point Y depends on:

– the constant TE at X;

– the constant TE introduced by network element i;

– the low-band dynamic TE at X;

– the dynamic TE introduced by network element i (low-band and high-band).

More generally, in a chain of time clocks, to a first order approximation:

– the constant TE, and link asymmetry, accumulates linearly;

– the low-band dynamic TE accumulates incoherently;

– the high-band dynamic TE is contributed mainly by the last element in the chain.

In a chain of time clocks, where the N nodes are indexed by the letter i, and the $(N-1)$ links are indexed by the letter j, the maximum absolute TE at the output of the Nth node can be upper bounded as:

$$\max|TE_N| \le \sum_{i=1}^{N}|cTE_i| + \sum_{j=1}^{N-1}|linkTE_j| + \sqrt{\left\{\sum_{i=1}^{N}\left[\max\left|d^L TE_i(t)\right|\right]^2\right\} + \left[\max\left|d^H TE_N(t)\right|\right]^2} \qquad \text{(IV-13)}$$

here $linkTE_j$ denotes the asymmetry of link j, RSS denotes the square root of the sum of the squares of the N low-band dynamic TE contributions from each node, and the high-band dynamic TE of the last (Nth) node.

With this construct, constant TE accumulates coherently (simple summation) and dynamic TE accumulates incoherently (square-root of sum of squares) for the low band; the high band dynamic TE is present only as the contribution from the last stage. Stated differently, the mean values of the various sources of TE accumulate linearly and the variances of the various sources of TE accumulate linearly.

Therefore, the performance specification of a network element should include the following:

– maximum allowed constant TE generation;

– maximum allowed low and high band dynamic TE generation;

– dynamic TE bandwidth range (min/max);

– minimum dynamic TE input tolerance.

Appendix V

Example of design options

(This appendix does not form an integral part of this Recommendation.)

V.1 Network limits

As described in Appendix IV, the network limits are expressed in terms of TE, and can be defined in one of three ways:

1)   the maximum absolute TE, max $|TE|$;

2)   the dynamic TE component, $dTE(t)$;

3)   the constant TE component cTE.

For example, the end application requirement, which for a long-term evolution (LTE) time division duplex (TDD) network is 1.5 µs, is an example of a maximum absolute TE limit. The MTIE mask in clause 7.3 is an example of a dynamic TE limit.

V.2 Components of time error budgets

A TE budget can be created for a network, working back from the end application requirement and subtracting the TE generation introduced by various components. The components of the budget to be considered depend on the design of the operator's network. They may include the following elements:

–   **Time error generation of the PRTC and T-GM**

The max|TE| permitted for an integrated PRTC/T-GM combination is 100 ns, as specified in [ITU-T G.8272]

–   **Dynamic time error of the network of T-BCs, $|dTE'|$**

The simulations performed have demonstrated that the maximum absolute dynamic TE, $|dTE'|$ is less than 200 ns for chains of up to 20 T-BCs.

(Refer to Appendices I and II for further information on these simulations)

–   **Constant time error of the T-BCs**

The constant TE, cTE, generated by a Type A T-BC is 50 ns or less. cTE adds linearly with the number of T-BCs, therefore the cTE generated by a chain of 10 Type A T-BCs is up to 500 ns.

Similarly, the constant TE, cTE generated by a Type B T-BC, is 20 ns or less; therefore, the cTE generated by a chain of 20 Type B T-BCs is up to 400 ns.

The cTE generated by a chain of clocks is denoted ce_{ptp_clocks}.

–   **Constant time error of the links between network elements**

The time offset estimation in PTP is unable to determine if the forward and reverse delays are asymmetric delays. Any difference in link delay between the forward and reverse directions will cause an error in a clock's calculation of time offset from master. This difference in delay may be caused by delays in the PHY component, different wavelengths used in each direction, or differences in the lengths of the forward fibre compared to the reverse fibre.

The cTE generated by the links in a chain is denoted ce_{link_asyms}.

–   **Transients caused by protection switching**

There are several different failure scenarios that can be considered, and these are described in [ITU-T G.8275]. For example, PHY-assisted holdover may be used in the T-GM, to keep

the internal clock "ticking" at a constant rate, or the PTP network may switch over to an alternative T-GM.

– **Noise generation of end application**

Some allowance must be made for noise generation in the end application. In the case of an eNodeB, this is normally considered to be 150 ns.

V.3 Failure scenarios

There are three main failure scenarios considered here.

a) Failures in the synchronization network that cause the end application clock to enter holdover for a short period. This is denoted TE_{REA} (rearrangement TE), which is provided by the end application, and is normally considered to be less than 250 ns.

– As an example, this might be triggered by a loss of PRTC traceability of one of the redundant T-GMs in the network. The loss of traceability is indicated by the clockClass field carried in the Announce messages indicating a degraded quality level, and triggers the BMCA to run. If the clockClass is set to a value that is unacceptable to the end application, then the clock will enter holdover for a short period (e.g., 1 min) prior to synchronizing to another T-GM.

b) Failures in the synchronization network that do not cause the end application clock to enter holdover. This is denoted TE_{HO} (holdover TE), which is provided by PRTC, and is normally considered to be less than 400 ns.

– As an example, this might be related to a short interruption of the GNSS signal (e.g., 5 min), causing the PRTC to go into holdover for a short period. During this period, either a PRC-traceable synchronous Ethernet signal or a stable internal oscillator might be used as a back-up to the PRTC. In this case, the clockClass field continues to indicate an acceptable quality level so that the end application clock stays locked to the PTP reference.

– This scenario is presented for information. It should be noted that the 1.1 µs network limit at reference point C defined in clause 7.3 might not be met. However, the 1.5 µs limit at reference point E should still be achieved.

c) Long interruption to the GNSS signal, with no alternative UTC-traceable T-GM available. The long-term holdover condition is handled as a special case where both the 1.1 µs limit at reference point C and the 1.5 µs limit at reference point E are exceeded. This is assumed to be a particularly rare event, and is presented for information.

The TE due to the holdover in this case, provided by PRTC, is assumed to be, in the worst case, 2 400 ns.

Further information on the protection scenarios and related budget is provided in this Appendix and in [ITU-T G.8275].

NOTE 1 – The end application is not required to handle long time synchronization holdover periods, but only short interruptions that could be caused by network rearrangements. Time synchronization and rearrangements that may happen in the network and that are modelled by TE_{HO} are included in the network limits. As a first approximation, TE_{REA} and TE_{HO} shall not be considered at the same time; in fact, TE_{REA} assumes that the end application enters holdover as soon as a failure is detected in the network, while TE_{HO} assumes that the end application continues to be locked to the incoming reference and in this case, there is no need to allocate a budget to TE_{REA}.

NOTE 2 – The time to restore (e.g., time to lock to a secondary time-synchronization reference) at the end application depends on the availability of physical frequency synchronization support and on the characteristics of the clock implemented in the end application.

a) Failures in the synchronization network that cause the end application clock to enter holdover for a short period. This is denoted TE_{REA} (rearrangement TE), which is provided by end application, and is normally considered to be less than 250 ns.

– As an example, this might be triggered by a loss of PRTC traceability of one of the redundant T-GMs in the network. The loss of traceability is indicated by the clockClass field carried in the Announce messages indicating a degraded quality level, and triggers the BMCA to run. If the clockClass is set to a value that is unacceptable to the end application, then the clock will enter holdover for a short period (e.g., 1 min) prior to synchronizing to another T-GM.

b) Failures in the synchronization network that do not cause the end application clock to enter holdover. This is denoted TE_{HO} (holdover TE), which is provided by PRTC, and is normally considered to be less than 400 ns.

– As an example, this might be related to a short interruption of the GNSS signal (e.g., 5 min), causing the PRTC to go into holdover for a short period. During this period, either a PRC-traceable synchronous Ethernet signal or a stable internal oscillator might be used as a back-up to the PRTC. In this case, the clockClass field continues to indicate an acceptable quality level so that the end application clock stays locked to the PTP reference.

c) Long interruption to the GNSS signal, with no alternative UTC-traceable T-GM available. The long-term holdover condition is handled as a special case where the 1.5 µs limit is exceeded. This is assumed to be a particularly rare event.

– The TE due to the holdover in this case, provided by PRTC, is assumed to be, in the worst case, 2 400 ns.

Further information on the protection scenarios and related budget is provided in this appendix and in [ITU-T G.8275].

NOTE 1 – The end application is not required to handle long time synchronization holdover periods, but only short interruptions that could be caused by network rearrangements. Time synchronization and rearrangements that may happen in the network and that are modelled by TE_{HO} are included in the network limits. As a first approximation, TE_{REA} and TE_{HO} shall not be considered at the same time; in fact, TE_{REA} assumes that the end application enters holdover as soon as a failure is detected in the network, while TE_{HO} assumes that the end application continues to be locked to the incoming reference and in this case there is no need to allocate a budget to TE_{REA}.

NOTE 2 – The time to restore (e.g., time to lock to a secondary time-synchronization reference) at the end application depends on the availability of physical frequency synchronization support and on the characteristics of the clock implemented in the end application.

V.4 Time error budget allocation

Table V.1 presents an example budget calculation related to the three failure scenarios.

The first scenario (a) refers to the normative network limits defined in clause 7.3.

For the purpose of information, additional scenarios (b) and (c) are also presented, where the network limits are not met.

In scenario (b), the 1.1 µs network limit at reference point C defined in clause 7.3 might not be met. However, the 1.5 µs limit at reference point E should still be achieved.

In scenario (c), the 1.1 µs network limit at reference point C defined in clause 7.3 will not be met, and the 1.5 µs limit at reference point E will also be exceeded.

Table V.1 – Example of time error allocation

Budget component	Failure scenario (a) (*T-GM rearrangement*)		Failure scenario (b) (*Short GNSS interruption*)		Failure scenario (c) (*Long holdover periods, e.g., 1 day*)	
PRTC (*ce*$_{ref}$)	100 ns		100 ns		100 ns	
Holdover and rearrangements in the network (*TE*$_{HO}$)	NA		400 ns		2 400 ns	
Random and error due to synchronous Ethernet rearrangements (*dTE*')	200 ns		200 ns		200 ns	
Node constant including intrasite (*ce*$_{ptp\_clock}$) (Note 1) (Note 2)	Type A 550 ns	Type B 420 ns	Type A 550 ns	Type B 420 ns	Type A 550 ns	Type B 420 ns
Link asymmetries (*ce*$_{link\_asym}$) (Note 3)	250 ns	380 ns	100 ns	230 ns	100 ns	230 ns
Total time error at reference point C (*TE*$_C$)	**1 100 ns**		**1 350 ns** (Note 4)		**3 350 ns**	
Rearrangements and short holdover in the end application (*TE*$_{REA}$)	250 ns		NA		NA	
End application (*TE*$_{EA}$)	150 ns		150 ns		150 ns	
Total time error at reference point E (*TE*$_E$)	**1 500 ns**		**1 500 ns**		**3 500 ns** (Note 5)	

NOTE 1 – For type A clocks, it is assumed in these examples that the clocks contribute a constant TE of 50 ns as per type A T-BC (see [ITU-T G.8273.2]).

In deployment case 1, the HRM is composed of: 1 T-GM, 10 Type A T-BCs, 1 T-TSC (embedded in the end application) and 11 links.

In deployment case 2, the HRM is composed of: 1 T-GM, 9 Type A T-BCs, 1 T-TSC, 10 links and 1 intra-site link. The TE budget allocated to the time synchronization distribution in the intra-site connection between the packet clock and the end application in the worst case is 50 ns. Therefore, the number of T-BCs is reduced by one to accommodate the extra TE resulting from the intra-site link.

NOTE 2 – For type B clocks, it is assumed in these examples that the clocks contribute a constant TE of 20 ns as per type B T-BC (see [ITU-T G.8273.2]).

In deployment case 1, the HRM is composed of: 1 T-GM, 20 T-BCs, 1 T-TSC and 21 links.

In deployment case 2, the HRM is composed of: 1 T-GM, 19 T-BCs, 1 T-TSC, 20 links and 1 intra-site link. The TE budget allocated to the time synchronization distribution in the intra-site connection between the packet clock and the end application in the worst case is 20 ns. Therefore, the number of T-BCs is reduced by one to accommodate the extra TE resulting from the intra-site link.

NOTE 3 – The link asymmetry budget is the remainder after any asymmetry compensation has been included.

NOTE 4 – Failure scenario (b) may cause the network limit of 1 100 ns at point C to be exceeded. This is for further study.

NOTE 5 – Exceeding the *TE*$_E$ limit of 1 500 ns may cause service degradation. The maximum frequency of occurrence of this scenario is governed by operator targets on service reliability.

Table V.1 presents an example budget calculation related to the three failure scenarios.

Table V.1 – Example of time error allocation

Budget component	Failure scenario (a) (*T-GM rearrangement*)		Failure scenario (b) (*Short GNSS interruption*)		Failure scenario (c) (*Long holdover periods, e.g., 1 day*)	
PRTC (ce_{ref})	100 ns		100 ns		100 ns	
Holdover and rearrangements in the network (TE_{HO})	NA		400 ns		2 400 ns	
Random and error due to synchronous Ethernet rearrangements (dTE'')	200 ns		200 ns		200 ns	
Node constant including intrasite (ce_{ptp_clock}) (Notes 1 and 2)	Type A 550 ns	Type B 420 ns	Type A 550 ns	Type B 420 ns	Type A 550 ns	Type B 420 ns
Link asymmetries (ce_{link_asym}) (Note 3)	250 ns	380 ns	100 ns	230 ns	100 ns	230 ns
Network limit at reference point C (TE_C)	1 100 ns		1 350 ns (Note 4)		3 350 ns	
Rearrangements and short holdover in the end application (TE_{REA})	250 ns		NA		NA	
End application (TE_{EA})	150 ns		150 ns		150 ns	
Total limit at reference point E (TE_E)	1 500 ns		1 500 ns		3 500 ns (Note 5)	

NOTE 1 – For type A clocks, it is assumed in these examples that the clocks contribute a constant TE of 50 ns as per type A T-BC (see [ITU-T G.8273.2]).

In deployment case 1, the HRM is composed of: 1 T-GM, 10 Type A T-BCs, 1 T-TSC (embedded in the end application) and 11 links.

In deployment case 2, the HRM is composed of: 1 T-GM, 9 Type A T-BCs, 1 T-TSC, 10 links and 1 intra-site link. The TE budget allocated to the time synchronization distribution in the intra-site connection between the packet clock and the end application in the worst case is 50 ns. Therefore the number of T-BCs is reduced by one to accommodate the extra TE resulting from the intra-site link.

NOTE 2 – For type B clocks, it is assumed in these examples that the clocks contribute a constant TE of 20 ns as per type B T-BC (see [ITU-T G.8273.2]).

In deployment case 1, the HRM is composed of: 1 T-GM, 20 T-BCs, 1 T-TSC and 21 links.

In deployment case 2, the HRM is composed of: 1 T-GM, 19 T-BCs, 1 T-TSC, 20 links and 1 intra-site link. The TE budget allocated to the time synchronization distribution in the intra-site connection between the packet clock and the end application in the worst case is 20 ns. Therefore the number of T-BCs is reduced by one to accommodate the extra TE resulting from the intra-site link.

NOTE 3 – The link asymmetry budget is the remainder after any asymmetry compensation has been included.

NOTE 4 – Failure scenario (b) may cause the network limit of 1 100 ns at point C to be exceeded. This is for further study.

Budget component	Failure scenario (a) (T-GM rearrangement)	Failure scenario (b) (Short GNSS interruption)	Failure scenario (c) (Long holdover periods, e.g., 1 day)
NOTE 5 – Exceeding the TE_E limit of 1 500 ns may cause service degradation. The maximum frequency of occurrence of this scenario is governed by operator targets on service reliability.			

V.5 Operator options

The budget presented in Table V.1 is an informative example, demonstrating how an operator can construct a TE budget for the network.

Each operator can construct their own budget along similar lines. For example, if an operator used a smaller network with fewer nodes, then ce_{ptp_clock} (the sum of the constant TE from each clock) could be reduced. This either leaves a greater margin, or allows the link asymmetry budget (ce_{link_asym}) to be increased.

Operators may also choose different protection strategies. Some may prefer using PRC-traceable frequency assisted holdover in the T-GMs (i.e., scenario B), while others may choose to distribute more T-GMs around the network for immediate fail-over to an alternative T-GM (i.e., scenario A).

V.6 Further details

As described in clauses V.1, V.2, V.3 and V.5, the network limits are expressed in terms of the maximum TE, max $|TE|$, and this is the result of two main components:

– the dynamic TE component, $dTE(t)$,

– the constant TE component cTE.

In order to take into account:

a) the internal noise sources of the end application, (indicated by TE_{EA}),

b) the residual noise caused by the dynamic TE component (indicated by dTE'),

c) a short holdover at the end application during rearrangements in the synchronization network (indicated by TE_{REA}), and

d) holdover in the synchronization network when the time reference is not available (indicated by TE_{HO}),

the network limit applicable at reference point C of deployment case 1 in Figure 7-1, expressed in terms of maximum absolute TE, must satisfy the following relationships:

For case a):

$$\max |TE_C| + TE_{EA} + TE_{REA} \leq \max|TE_E| \qquad \text{(V-1a)}$$

with:

$$|(cTE + dTE')| \leq \max |TE_C| \qquad \text{(V-2a)}$$

For case b):

$$\max |TE_C| + TE_{EA} \leq \max|TE_E| \qquad \text{(V-1b)}$$

with:

$$|(cTE + dTE')| + TE_{HO} \leq \max |TE_C| \qquad \text{(V-2b)}$$

In Formulae (V-1a) and (V-1b), TE_E indicates the network limit at reference point E expressed in terms of maximum absolute TE, TE_{HO} represents the budget allocated to holdover and rearrangements in the network and $|dTE'|$ is the maximum absolute value of a filtered version of the dynamic TE

component $dTE(t)$. In practice, dTE' estimates the dynamic component of the TE at the output of the end application.

NOTE 1 – The network limit at reference point D of deployment case 2 in Figure 7-2 is similar to Formulae (V-1a), (V-1b), (V-2a) and (V-2b), except that TE_D replaces TE_C.

NOTE 2 – The end application is not required to handle long time synchronization holdover periods, but only short interruptions that could be caused by network rearrangements. Time synchronization and rearrangements that may happen in the network and that are modelled by TE_{HO} are included in the network limits. As a first approximation, TE_{REA} and TE_{HO} shall not be considered at the same time; in fact, TE_{REA} assumes that the end application enters holdover as soon as a failure is detected in the network, while TE_{HO} assumes that the end application continues to be locked to the incoming reference and, in this case, there is no need to allocate a budget to TE_{REA}.

NOTE 3 – The terms cTE and dTE' in the previous relationship are not measured separately, but indicate the components that build max $|TE|$. In the worst case, cTE and dTE' are both of the same polarity, but in a specific deployment they may partly compensate each other if the polarity is different.

The simulations performed show that is possible to limit $|dTE'|$ to 200 ns or less (i.e., in the worst case $|dTE'| = 200$ ns), and this value is considered in the TE budgeting analysis. Refer to Appendices I and II for further information on these simulations.

NOTE 4 – In order to meet the noise limit for the end application at reference point E, TE_E, the end application shall tolerate a certain amount of noise at its input (reference point C of deployment case 1 in Figure 7-1, or reference point D of deployment case 2 in Figure 7-1). If $dTE(t)$ exceeds the target limit of 200 ns, the end application should provide appropriate filtering to reduce the noise at reference point D to the value of dTE', expressed in terms of maximum absolute TE. Further information is provided in Appendix VI.

NOTE 5 – The time to restore (e.g., time to lock to a secondary time-synchronization reference) at the end application depends on the availability of physical frequency synchronization support and on the characteristics of the clock implemented in the end application.

Based on Formulae (V-1a) and (V-2a), Formula (V-3a) applies for case a),

$$|cTE| \leq TE_E - (TE_{EA} + TE_{REA} + dTE') \tag{V-3a}$$

And based on Formulae (V-1b) and (V-2b), Formula (V-3b) applies for case b),

$$|cTE| \leq TE_E - (TE_{EA} + TE_{HO} + dTE') \tag{V-3b}$$

According to the assumption that $TE_E = 1\,500$ ns, $TE_{EA} = 150$ ns, $TE_{REA} = 250$ ns, $TE_{HO} = 400$ ns and $dTE' = 200$ ns, Formula (V-4a) applies for case a),

$$|cTE| \leq 1\,500\text{ ns} - (150\text{ ns} + 250\text{ ns} + 200\text{ ns}) = 900\text{ ns} \tag{V-4a}$$

and Formula (V-4b) applies for case b),

$$|cTE| \leq 1\,500\text{ ns} - (150\text{ ns} + 400\text{ ns} + 200\text{ ns}) = 750\text{ ns} \tag{V-4b}$$

The constant TE component cTE is due to static contributions to the TE, mainly related to link asymmetries and PTP clock (T-BC, T-GM and T-TSC) constant TE accumulation.

NOTE 6 – cTE can be considered approximately constant over time assuming there are no changes in the network (e.g., re-routing).

In particular cTE can be expressed as follows:

$$|cTE| = ce_{ref} + ce_{ptp\_clocks} + ce_{link\_asyms} \tag{V-5}$$

where ce_{ref} is the accuracy of the PRTC as specified in [ITU-T G.8272], ce_{ptp_clocks} is the sum of PTP clocks' constant TEs, which are defined as part of the T-BC specification, and ce_{link_asyms} is the overall TE due to link asymmetries. ce_{ptp_clocks} for a number, m, of PTP clocks (T-GM, T-BC or T-TSC) in a chain can be expressed as follows:

$$ce_{ptp\_clocks} = \sum_{n=1}^{m} ce_{ptp\_clock,n} \tag{V-6}$$

where $ce_{ptp\_clock,n}$ is the constant TE for the nth PTP clock.

ce_{link_asyms} for $m+1$ number of links can be expressed as follows:

$$ce_{link\_asyms} = \sum_{n=1}^{m+1} ce_{link\_asym,n} \tag{V-7}$$

where $ce_{link\_asym,n}$ is the TE due to link asymmetry for the nth link.

Assuming a level of accuracy 4 as per Table 1 of [ITU-T G.8271] (i.e., $TE_E = 1.5\,\mu s$) and $ce_{ref} = 100$ ns, Formula (V-8a) applies for case a):

$$cTE = ce_{ref} + ce_{ptp\_clocks} + ce_{link\_asyms} \leq 900 \text{ ns} \tag{V-8a}$$

and therefore:

$$ce_{ptp\_clocks} + ce_{link\_asyms} \leq 800 \text{ ns} \tag{V-9a}$$

and Formula (V-8b) applies for case b):

$$cTE = ce_{ref} + ce_{ptp\_clocks} + ce_{link\_asyms} \leq 750 \text{ ns} \tag{V-8b}$$

and therefore,

$$ce_{ptp\_clocks} + ce_{link\_asyms} \leq 650 \text{ ns} \tag{V-9b}$$

For the case of an HRM of 10 T-BCs, of constant TE of 50 ns (T-BC with constant TE class A, see [ITU-T G.8273.2]) and assuming that the constant TE for the T-GM also is 50 ns, this leads to:

$$ce_{ptp\_clocks} = 50 \text{ ns} + (10 \times 50 \text{ ns}) = 550 \text{ ns} \tag{V-10}$$

And, for the case of an HRM of 20 T-BCs, of constant TE of 20 ns (T-BC with constant TE class B, see [ITU-T G.8273.2]), and assuming that the constant TE for the T-GM also is 20 ns, this leads to:

$$ce_{ptp\_clocks} = 20 \text{ ns} + (20 \times 20 \text{ ns}) = 420 \text{ ns} \tag{V-11}$$

Then the fibre asymmetry budget for case a), with a T-BC of class A of [ITU-T G.8273.2], is:

$$ce_{link\_asyms} \leq 250 \text{ ns} \tag{V-12a-1}$$

and with a T-BC of class B of [ITU-T G.8273.2] is:

$$ce_{link\_asyms} \leq 380 \text{ ns} \tag{V-12a-2}$$

The fibre asymmetry budget for case b) with a T-BC of class A of [ITU-T G.8273.2] is:

$$ce_{link\_asyms} \leq 100 \text{ ns} \tag{V-12b-1}$$

and with a T-BC of class B of [ITU-T G.8273.2] is:

$$ce_{link\_asyms} \leq 230 \text{ ns} \tag{V-12b-2}$$

Appendix VI

Mitigation of time error due to synchronous Ethernet transients

(This appendix does not form an integral part of this Recommendation.)

Clause II.1.2 illustrates HRMs for the transport of phase/time via PTP with PHY frequency support. Figure II.3 illustrates the congruent scenario, where the frequency and phase/time transports follow the same synchronization path. Figure II.4 illustrates the non-congruent scenario, where the frequency and phase/time transports follow different synchronization paths. A rearrangement of the PHY frequency, e.g., synchronous Ethernet, transport results in phase/time error at each T-BC, the T-TSC, and the end application. The TE is generally larger in the congruent scenario than in the non-congruent scenario, because in the congruent scenario each T-BC has errors due to the rearrangement transient in both the time and frequency planes. The latter occurs in the PHY frequency input to a T-BC, and the former occurs in PTP Sync messages input to a T-BC from the upstream T-BC. In the non-congruent scenario, a T-BC has an error due only to the PHY frequency input (assuming that only one synchronous Ethernet reference chain at a time undergoes a rearrangement).

Details on requirements and solutions to address this issue are provided in [ITU-T G.8273.2].

NOTE 1 – In the case where in the congruent scenario the T-BC does not comply with Annex B of [ITU-T G.8273.2], the TE due to the synchronous Ethernet rearrangement can be reduced to an acceptable level by using an end application clock with sufficiently narrow bandwidth and sufficiently small gain peaking, and by collocating a suitable clock with the end application in the frequency plane. Simulations have shown that for the HRM of Appendix II, a maximum end application clock bandwidth of 0.005 Hz, with a maximum gain peaking of 0.1 dB, can reduce the TE due to the synchronous Ethernet rearrangement to an acceptable level. The analysis was done assuming an ITU-T G.812-type I clock is collocated with the end application clock in the frequency plane; however, a different type of clock might still result in an acceptable TE. This has not been verified.

In the non-congruent scenario, the TE will be acceptable if the T-BCs, T-TSC, and end application have minimum bandwidth of 0.05 Hz, maximum bandwidth of 0.1 Hz and maximum gain peaking of 0.1 dB, and if the frequency plane clocks collocated with the T-BCs, T-TSC, and end application are EECs. This is true whether or not the synchronous Ethernet transient is rejected at each T-BC.

NOTE 2 – The case of a network where a synchronization status message (SSM) is not used is for further study.

Appendix VII

Maximum relative time error

(This appendix does not form an integral part of this Recommendation.)

Time errors (accuracy) could also be expressed in terms of maximum relative time error, rather than maximum absolute time error, which is described in Appendix IV. However, in order to calculate the relative time error, it is necessary to calculate the absolute time error as well.

Now, in order to calculate the maximum relative time error accuracy, one approach to illustrating the accumulation of relative time error is described with reference to Figure VII.1.
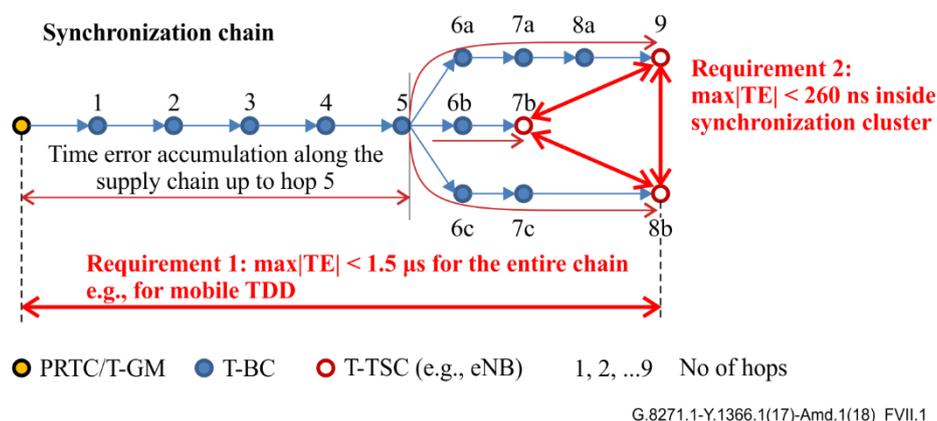
Figure VII.1 – Illustration of relative time error

In Figure VII.1, nodes 1 to 5 represent the joint part of the synchronization supply chain, which is common for all base stations. Nodes 5 to 6(a, b, c)/7(a, b, c)8(a, b)/9 represent the part of the synchronization supply chain that is used for the specific base station only (which is part of the base station cooperation cluster). Time error components from the common used synchronization chain, such as cTE, do influence all base stations of the synchronization cluster in the same way. That is, in the examples shown in Figure VII.1, the entire chain (at the output of the end application) requires 1.5 µs as max|TE| due to TDD operation (level of accuracy 4 in Table 1 in [ITU-T G.8271]). In addition, taking as an example class 6A as shown in Table 2 of [ITU-T G.8271], a maximum relative time error of 260 ns maximum deviation between the end applications is required inside the synchronization cluster.

From Figure VI.1, the maximum absolute time error at reference points 5/6(a, b, c)/7(a, b, c)/8(a, b)/9 is:

$$\max|TE_X(t)| = \max|cTE_X + dTE_X(t)| \tag{VII-1}$$

where X represents the reference points 5/6(a, b, c)/7(a, b, c)/8(a, b))/9 at which the maximum absolute time error is measured. Now, the maximum relative time error is related to the maximum deviation (time error) between adjacent base stations that are present in the same synchronization cluster, obtaining their frequency and phase synchronization from the same source for the last network elements in the chain.

Firstly, the relative time error between node X and node Y is,

$$TE_{xy}(t) = TE_x(t) - TE_y(t) \tag{VII-2}$$

And, the maximum absolute relative time error is,

$$\max|TE_{xy}(t)| = \max|TE_x(t) - TE_y(t)| \tag{VII-3}$$

In addition, the maximum time error can be also denoted by Eq. (VII-4) and Eq. (VII-5)

$$TE_x(t) = TE_z(t) + TE_{xz}(t) \qquad \text{or} \quad TE_{xz}(t) = TE_x(t) - TE_z(t) \qquad (VII\text{-}4)$$

$$TE_y(t) = TE_z(t) + TE_{yz}(t) \qquad \text{or} \quad TE_{yz}(t) = TE_y(t) - TE_z(t), \qquad (VII\text{-}5)$$

where:

$TE_z(t)$, $TE_x(t)$ and $TE_y(t)$ are the absolute time errors at node Z, node X and node Y, respectively. The node Z, e.g., node 5 in Figure VI.1, connects with both node X and node Y, and

$TE_{xz}(t)$ is the relative time error between node X and node Z,

$TE_{yz}(t)$ is the relative time error between node X and node Z.

Substituting Eq. (VII-4) and Eq. (VII-5) into Eq. (VI-2) gives

$$TExy(t) \qquad = TEx(t) - TEy(t)$$

$$= (TEz(t) + TExz(t)) - (TEz(t) + TEyz(t))$$

$$= TExz(t) - TEyz(t) \qquad (VII\text{-}6)$$

Then, the maximum absolute relative time error is

$$\max|TE_{xy}(t)| = \max|TE_x(t) - TE_y(t)|$$

$$= \max|TE_{xz}(t) - TE_{yz}(t)| \qquad (VII\text{-}7)$$

A well-known property of inequalities involving real numbers is

$$|u - v| \le |u| + |v| \qquad (VII\text{-}8)$$

for any real numbers u and v.

Then:

$$|TE_{xz}(t) - TE_{yz}(t)| \le |TE_{xz}(t)| + |TE_{yz}(t)| \qquad (VII\text{-}9)$$

and:

$$\max|TE_{xz}(t) - TE_{yz}(t)| \le \max(|TE_{xz}(t)| + |TE_{yz}(t)|) \qquad (VII\text{-}10)$$

In addition, for any two real-valued functions, $f(t)$ and $g(t)$:

$$\max\big(f(t) + g(t)\big) \le \max\big(f(t)\big) + \max\big(g(t)\big) \qquad (VII\text{-}11)$$

Then, using Eq. (VII-11) in Eq. (VI-10) produces:

$$\max|TE_{xz}(t) - TE_{yz}(t)| \le \max|TE_{xz}(t)| + \max|TE_{yz}(t)|). \qquad (VII\text{-}12)$$

TEs (accuracy) could also be expressed in terms of maximum relative TE, rather than maximum absolute TE, which is described in Appendix IV. However, in order to calculate the relative TE, it is also necessary to calculate the absolute TE.

Now, in order to calculate the maximum relative TE accuracy, one approach to illustrating the accumulation of relative TE is described with reference to Figure VII.1.
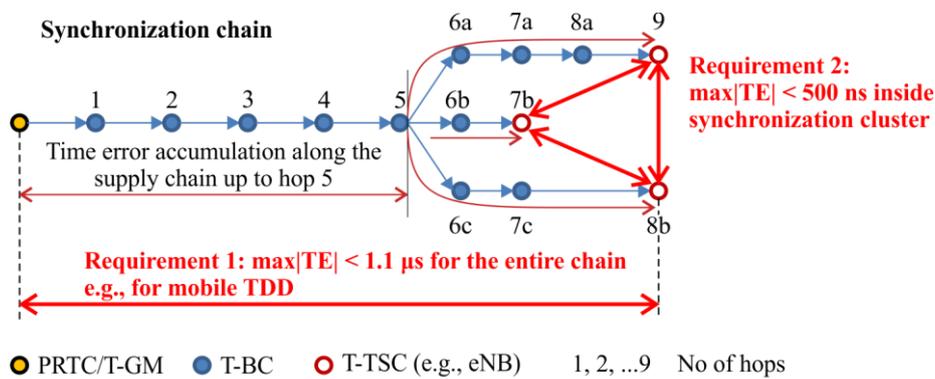
Figure VII.1 – Illustration of relative time error

In Figure VII.1, nodes 1 to 5 represent the joint part of the synchronization supply chain, which is common for all base stations. Nodes 5 to 6(a, b, c)/7(a, b, c)/8(a, b)/9 represent the part of the synchronization supply chain that is used for the specific base station only (which is part of the base station cooperation cluster). TE components from the common nodes in the synchronization chain (e.g., nodes 1 to 5 in the example shown in Figure VII.1)), such as cTE, do influence all base stations of the synchronization cluster in the same way. That is, from Figure VII.1, the entire chain requires 1.1 µs as max|TE| for the entire chain due to TDD operation, In addition, a maximum relative TE of 500 ns maximum deviation between the end applications is required inside the synchronization cluster.

From Figure VII.1, the maximum absolute TE at reference points 5/6(a, b, c)/7(a, b, c)/8(a, b)/9 is:

$$\max|TE_X(t)| = \max|cTE_X + dTE_X(t)| \qquad (VII-1)$$

where X represents the reference points 5/6(a, b, c)/7(a, b, c)/8(a, b))/9 at which the maximum absolute TE is measured. Now, the maximum relative TE is related to the maximum deviation (TE) between adjacent base stations that are present in the same synchronization cluster, obtaining their frequency and phase synchronization from the same source for the last network elements in the chain.

Firstly, the relative TE between node X and node Y is,

$$TE_{XY}(t) = TE_X(t) - TE_Y(t) \qquad (VII-2)$$

And, the maximum absolute relative TE is,

$$\max|TE_{XY}(t)| = \max|TE_X(t) - TE_Y(t)| \qquad (VII-3)$$

In addition, the maximum TE can be also denoted by Formulae (VII-4) and (VII-5)

$$TE_X(t) = TE_Z(t) + TE_{XZ}(t) \qquad \text{or } TE_{XZ}(t) = TE_X(t) - TE_Z(t) \qquad (VII-4)$$

$$TE_Y(t) = TE_Z(t) + TE_{YZ}(t) \qquad \text{or } TE_{YZ}(t) = TE_Y(t) - TE_Z(t) \qquad (VII-5)$$

where:

$TE_Z(t), TE_X(t)$ and $TE_Y(t)$ are the absolute TEs at node Z, node X and node Y, respectively. The node Z, e.g., node 5 in Figure VII.1, connects with both node X and node Y, and

    $TE_{XZ}(t)$ is the relative TE between node X and node Z,

    $TE_{YZ}(t)$ is the relative TE between node X and node Z.

Substituting Formulae (VII-4) and (VII-5) into Formula (VI-2) gives:

$$TE_{XY}(t) \qquad = TE_X(t) - TE_Y(t)$$

$$= (TEZ(t) + TEXZ(t)) - (TEZ(t) + TEYZ(t))$$

$$= TE_{XZ}(t) - TE_{YZ}(t) \qquad (VII-6)$$

Then, the maximum absolute relative TE is:

$$\max|TE_{XY}(t)| = \max|TE_X(t) - TE_Y(t)|$$

$$= \max|TE_{XZ}(t) - TE_{YZ}(t)| \qquad \text{(VII-7)}$$

A well-known property of inequalities involving real numbers is:

$$|u - v| \leq |u| + |v| \qquad \text{(VII-8)}$$

for any real numbers u and v.

Then:

$$|TE_{XZ}(t) - TE_{YZ}(t)| \leq |TE_{XZ}(t)| + |TE_{YZ}(t)| \qquad \text{(VII-9)}$$

and:

$$\max|TE_{XZ}(t) - TE_{YZ}(t)| \leq \max(|TE_{XZ}(t)| + |TE_{YZ}(t)|) \qquad \text{(VII-10)}$$

In addition, for any two real-valued functions, $f(t)$ and $g(t)$:

$$\max(f(t) + g(t)) \leq \max(f(t)) + \max(g(t)) \qquad \text{(VII-11)}$$

Then, using Formula (VII-11) in Formula (VII-10) produces:

$$\max|TE_{XZ}(t) - TE_{YZ}(t)| \leq \max|TE_{XZ}(t)| + \max|TE_{YZ}(t)|) \qquad \text{(VII-12)}$$

Appendix VIII

Models for budgeting in a chain of microwave devices

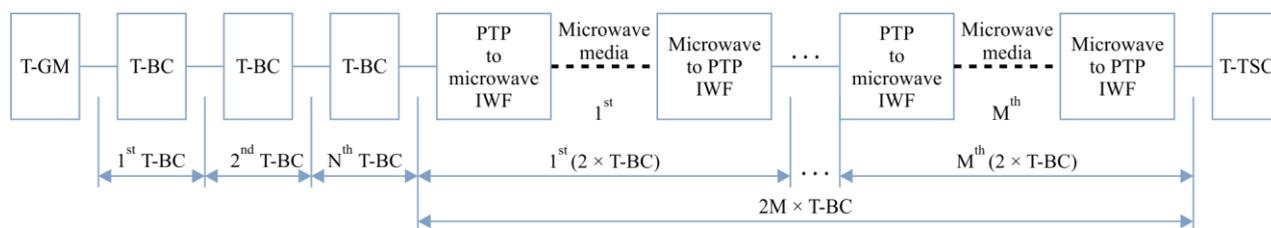(This appendix does not form an integral part of this Recommendation.)

Figures VIII.1 and VIII.2 show the topology to be considered when developing budgets for chains of microwave equipment functioning as chains of T-BCs.
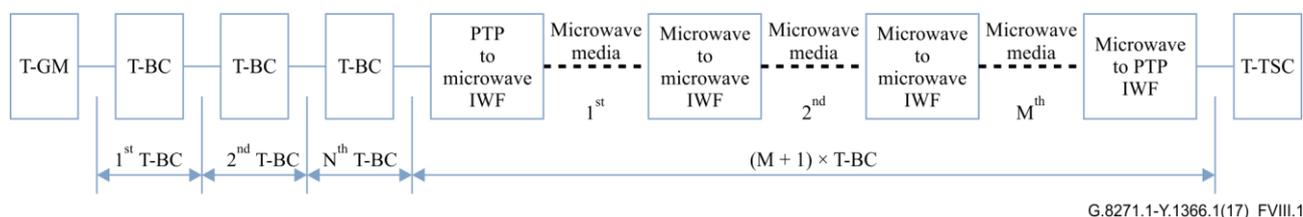
G.8271.1-Y.1366.1(17)_FVIII.1

**Figure VIII.1 – Network reference model for phase/time synchronization over
M microwave hops**

The case of cascaded microwave links, where microwave links are alternated with Ethernet-based equipment or in general where the microwave equipment is connected via Ethernet and PTP is carried over Ethernet, can be modelled by Figure VIII.2 showing *N* cascaded T-BCs combined with *M* microwave links.

G.8271.1-Y.1366.1(17)_FVIII.2

**Figure VIII.2 – Network reference model for phase/time synchronization over *M* microwave
hops, including intermediate conversion between microwave and Ethernet**

NOTE 1 – Similar topology can be considered when developing budgets for chains of microwave equipment functioning as chains of T-TCs (i.e., replacing T-BC with T-TC in Figures VIII.1 and VIII.2).

NOTE 2 – This does not require that each microwave device (transmitter, repeater or receiver) must function as a PTP BC or TC. The equivalence to a T-BC or T-TC is purely for performance estimation purposes as part of the HRM.

Figure VIII.3 shows an example of equipment that is transferring timing flow from native PTP to native access media, such as microwave equipment. Only one PTP port and one special port are shown in Figure VIII.3, although the equipment may contain multiple ports.
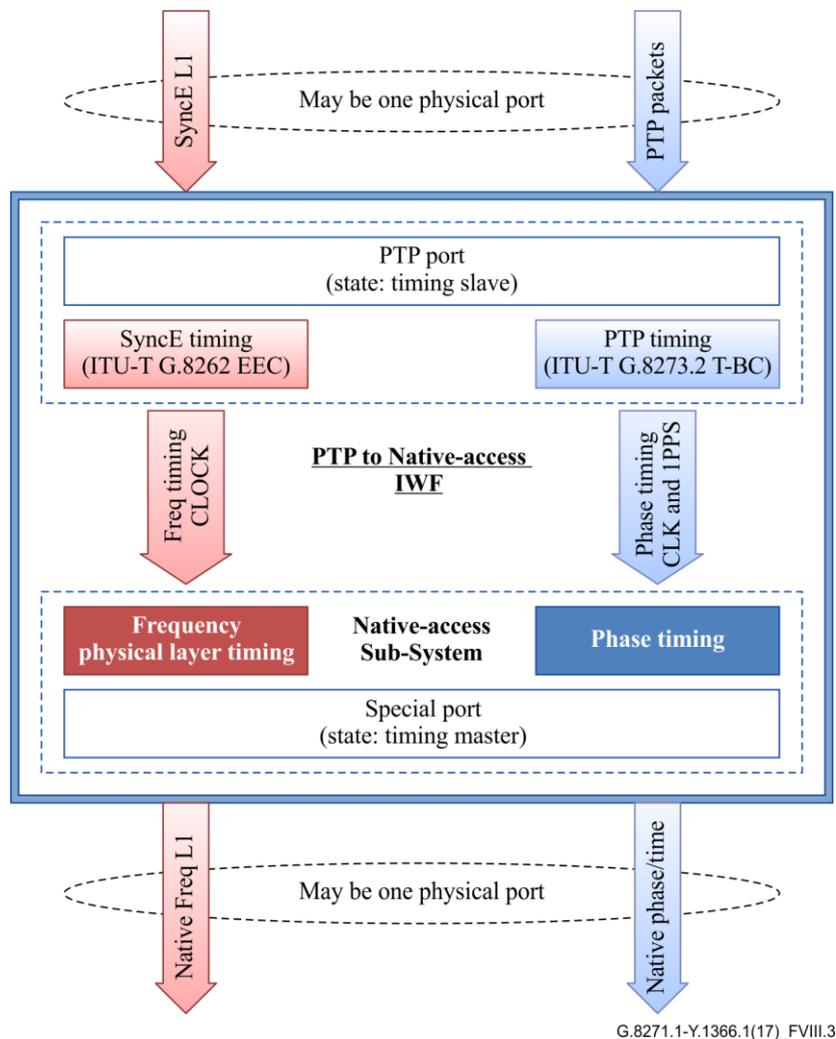
Figure VIII.3 – Timing flow from PTP to native access media (either direction)

NOTE – In Figure VIII.3, an example is given with one physical port on each side.

Figure VIII.4 shows an example of equipment that is transferring timing flow from native access media to PTP, such as microwave equipment. Only one PTP port and one special port are shown in Figure VIII.4, although the equipment may contain multiple ports.
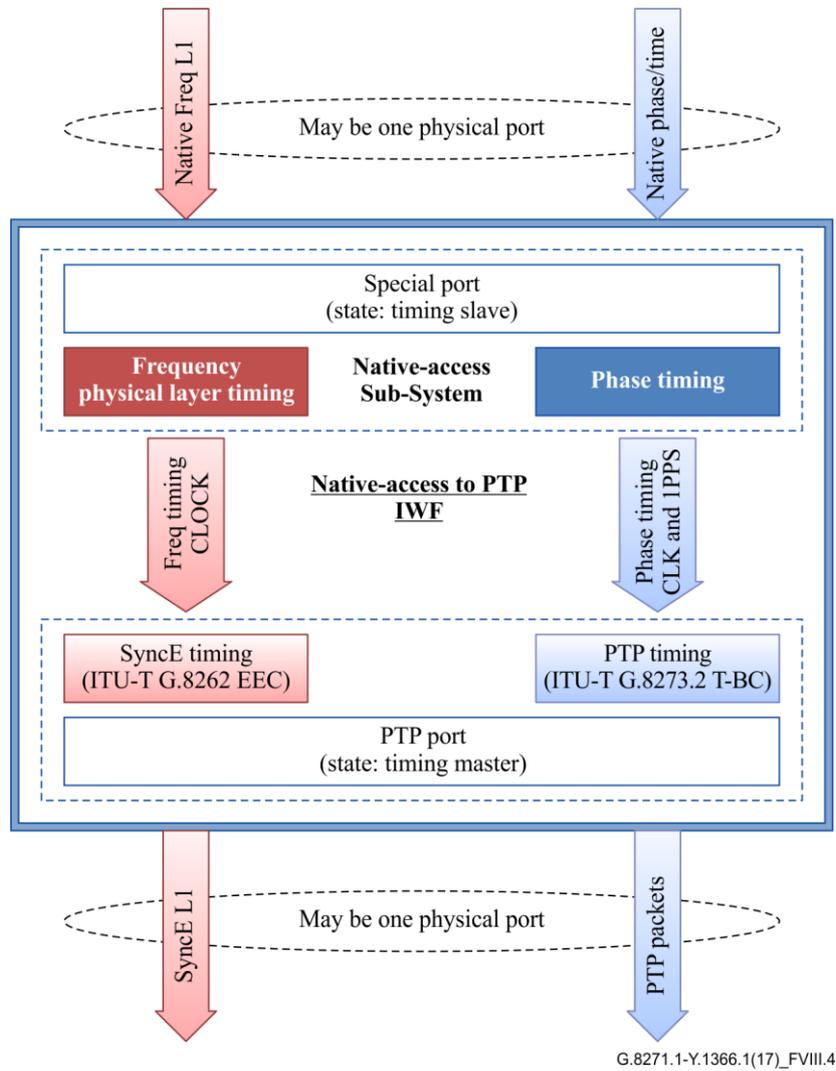
Figure VIII.4 – Timing flow from native access media to PTP (either direction)

NOTE – In Figure VIII.4, an example is given with one physical port on each side.

Appendix IX

Models for budgeting in a chain of xPON or xDSL devices

(This appendix does not form an integral part of this Recommendation.)

Figure IX.1 shows the topology to be considered when developing budgets for chains of native access equipment (such as xPON or xDSL) functioning as chains of T-BCs.
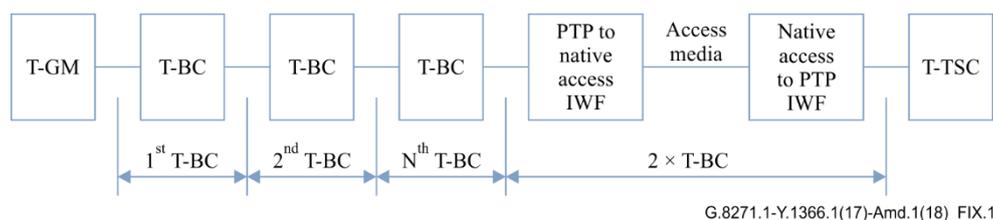

Figure IX.1 – Network reference model for phase/time synchronization over native access media

As shown in Figure IX.1, the same performance budget of the equivalent of two T-BCs may be used when developing performance budgets for access systems, e.g., xPON or xDSL. This is purely for performance estimation purposes; it does not mean that each unit (e.g., optical line terminal (OLT) and optical network terminal (ONT) in a gigabit-capable passive optical network (GPON) system) has to actually function as a PTP BC.

When measuring the performance of a GPON system, it should be fully loaded with ONTs for worst case noise generation.

Figure IX.2 shows an example of equipment that is transferring timing flow from native PTP to native access media, such as xPON OLT or xDSL digital subscriber line access multiplexer (DSLAM) equipment. Only one PTP port and one special port are shown in Figure IX.2, although the equipment may contain multiple ports.
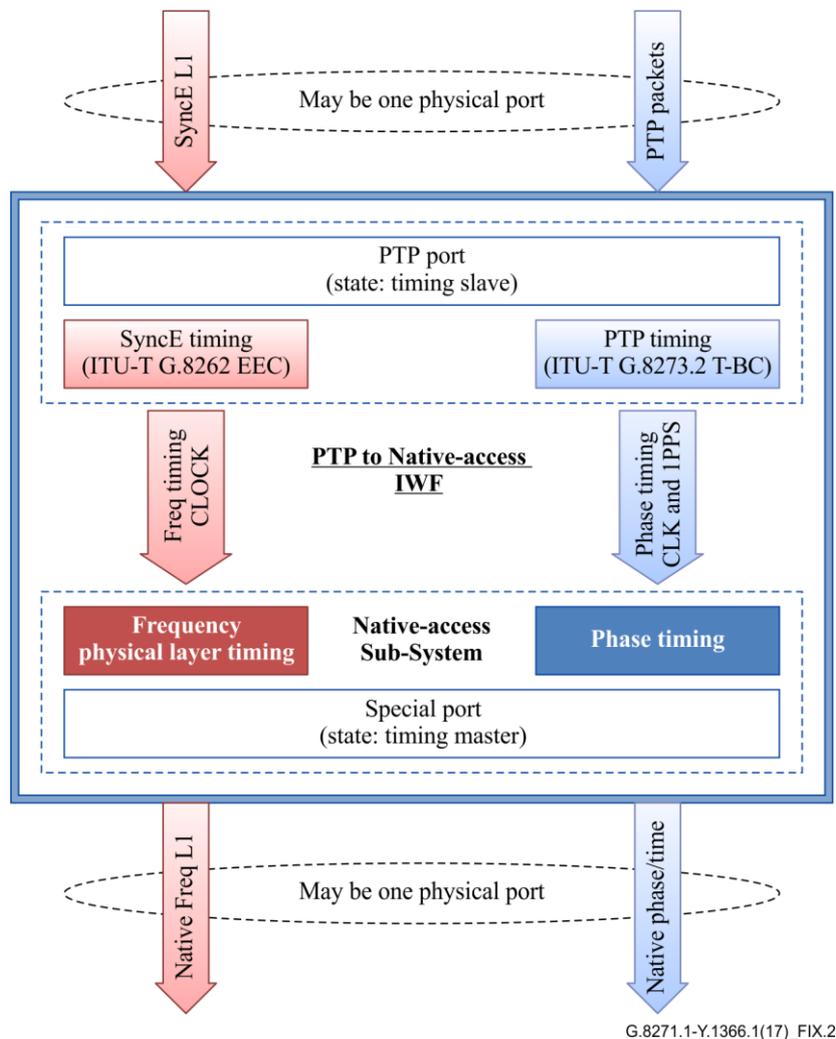
Figure IX.2 – Timing flow from PTP to native access media (downstream)

NOTE – In Figure IX.2, an example is given with one physical port on each side.

Figure IX.3 shows an example of equipment that is transferring timing flow from native access media to PTP, such as xPON ONU or xDSL remote terminal-digital subscriber line access multiplexer (RT-DSLAM) equipment. Only one PTP port and one special port are shown in Figure IX.3, although the equipment may contain multiple ports.
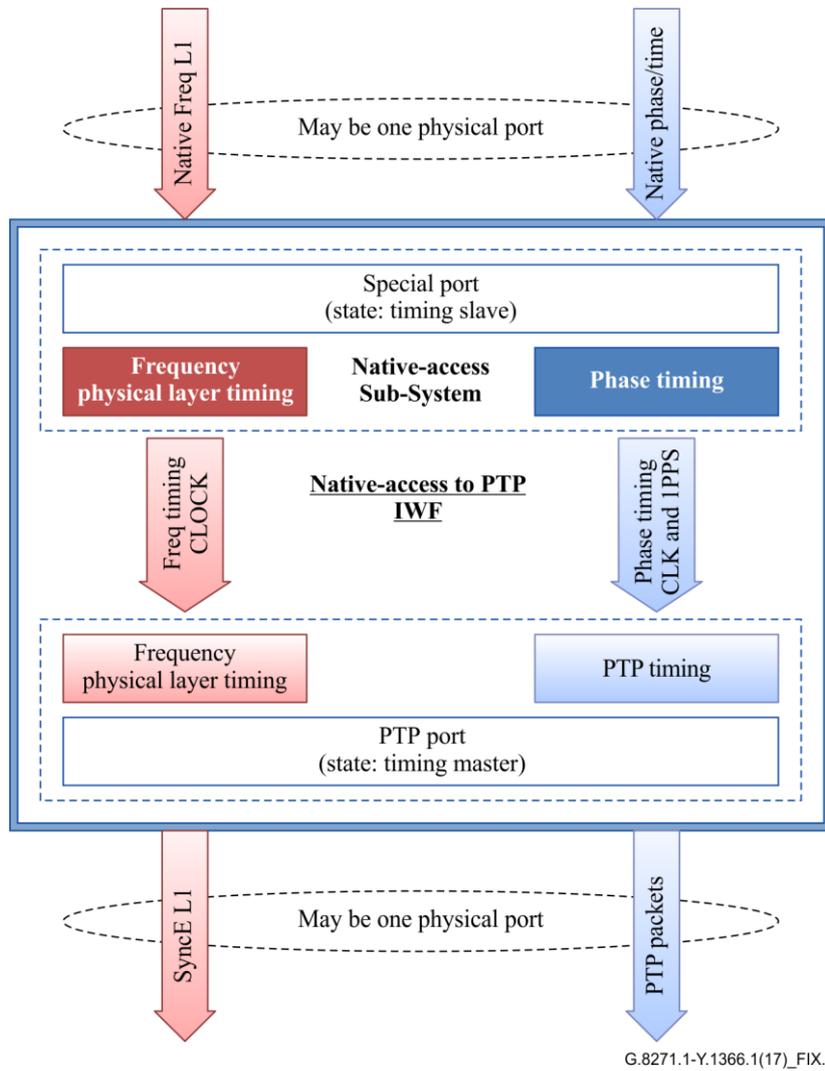
G.8271.1-Y.1366.1(17)_FIX.3

Figure IX.3 – Timing flow from native access media to PTP (downstream)

NOTE – In Figure IX.3, an example is given with one physical port on each side.

Appendix X

Time error and transients due to PTP rearrangement

(This appendix does not form an integral part of this Recommendation.)

A rearrangement of the phase/time transport occurs when a T-BC loses its phase/time input (PTP) and switches to alternate master/PTP input while continuing to receive its frequency input (SyncE). This alternate PTP input switchover may result in phase/time error and/or transient at the T-BC, any downstream PTP clocks, and at the end application.

The phase/time error and/or transient after switching to an alternate PTP input may be significant. Factors affecting the phase/time error and/or transient include different link, node and path delays and/or asymmetries on the alternate PTP input clock path back to the PRTC source compared with the original PTP input clock path to its PRTC source.

Details on requirements and solutions to address this issue are for further study in the relevant recommendation (e.g., requirements on the T-BC in [ITU-T G.8273.2].

Appendix XI

Measurement of maximum relative time error limits

(This appendix does not form an integral part of this Recommendation.)

XI.1 Measurement of maximum relative time error limits

Appendix VII describes the concept of maximum relative time error between the nodes of a synchronization network. The measurement of maximum relative time error limits requires measurement equipment with a common time reference at each point in the network where the measurement is to be made. This may be physically impossible if the two points are geographically separated, although it may be possible in a laboratory situation, or if the two points are close.

XI.1.1 Measurement in a laboratory environment

In this situation, a single piece of measurement equipment with multiple inputs is required to measure at two separate points and compare the time error at each point.

This can be done in two ways:

1)   Using the input from one point as the time reference to the measurement equipment, and measuring the other points with respect to this reference;

2)   Measuring the time error from each point with respect to the internal time reference of the measurement equipment, and then subtracting time error of one point from the other. The measurement equipment does not require to use the same time reference as the system under test, since any difference will cancel in the subtraction process.

Figure XI.1 shows the second method, using tapped monitoring as in Figure III.2. Both active probe monitoring and 1 PPS measurement (as described in Appendix III) could also be used in a similar configuration, as shown in Figures XI.2 and XI.3. If the end application also generates a 1 PPS output for measurement purposes, this could be used instead of the 1 PPS output of the T-BC.

The figures below do not make any assumptions about the number of T-BCs deployed in the network. In these figures, the dotted line denoted C corresponds to reference point C in Figure 7-1. All cable delays between the T-BC and the measurement equipment must be carefully measured and compensated for in order to obtain the best accuracy possible. In addition, for PTP connections the delay asymmetry should be measured and compensated for.
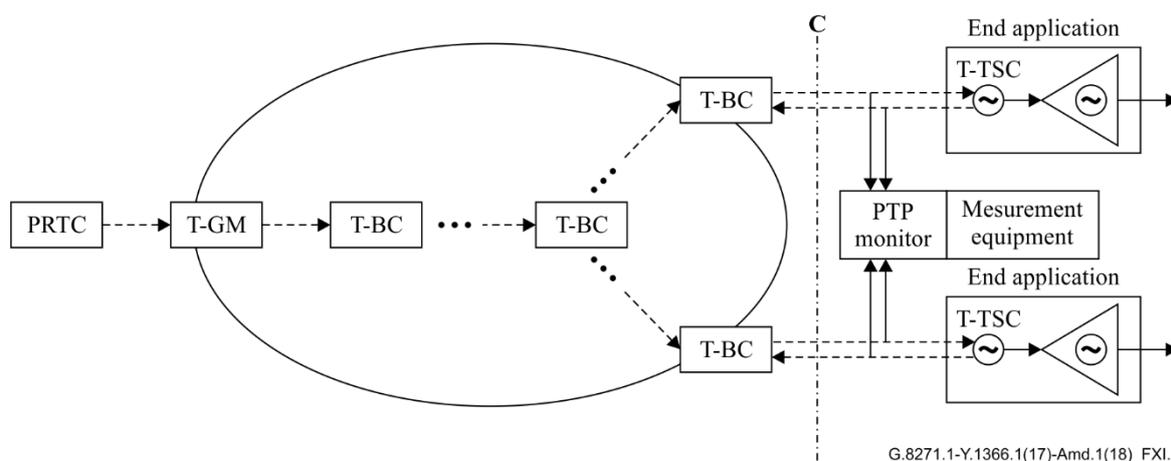

G.8271.1-Y.1366.1(17)-Amd.1(18)_FXI.1

Figure XI.1 – Maximum relative time error measurement in a laboratory environment, using the tapped monitoring technique
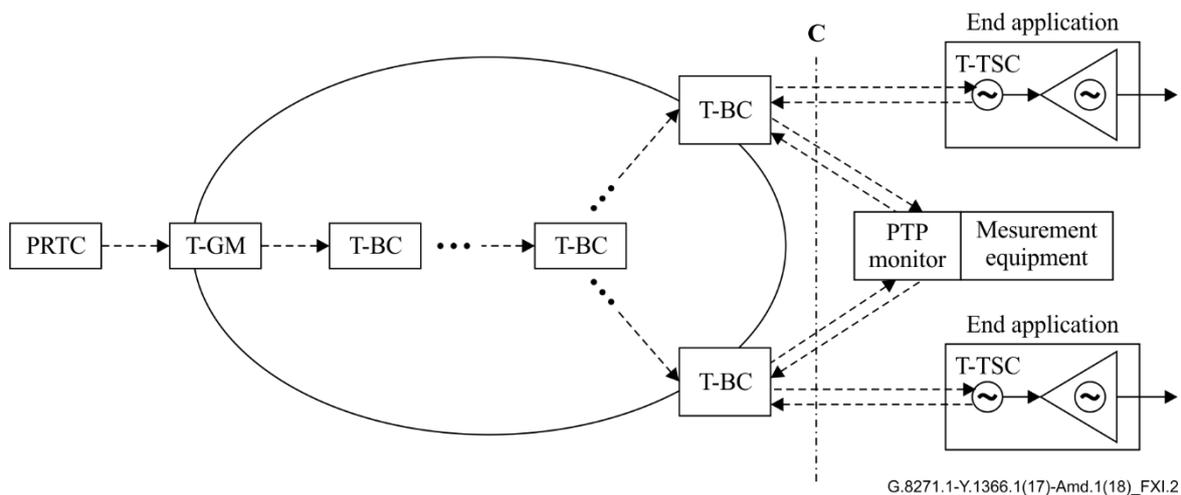
Figure XI.2 – Maximum relative time error measurement in a laboratory environment, using the active probe monitoring technique
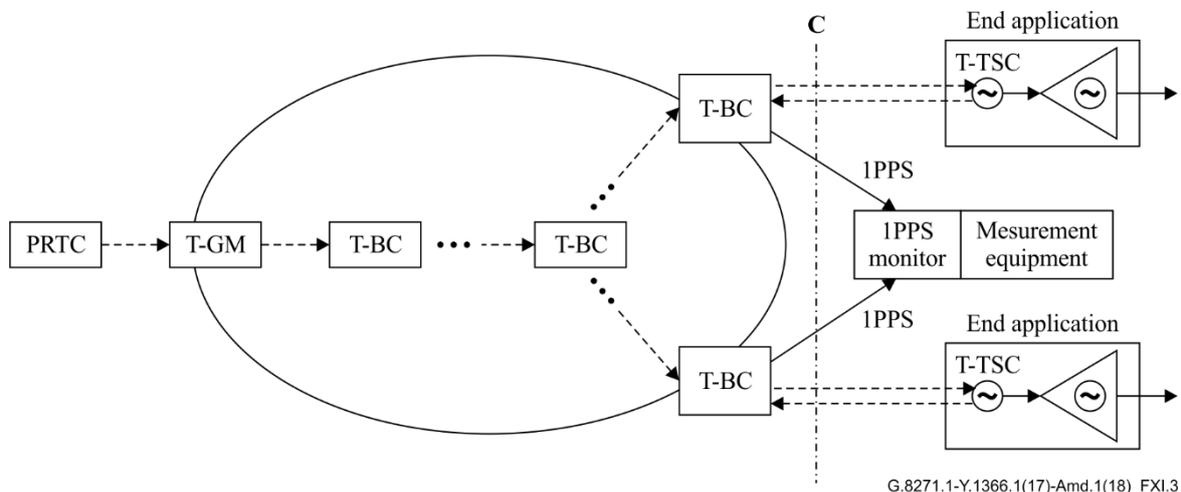

Figure XI.3 – Maximum relative time error measurement in a laboratory environment, using the 1 PPS monitoring technique

XI.1.2 Measurement in a field environment

In this situation, the two points being measured are geographically separated, such that is not possible to use a single piece of measurement equipment. The procedure is to make two separate simultaneous time error measurements, and subtract one from the other.

In order to make measurements that can be compared, the two pieces of measurement equipment will need to be referenced to the same time reference. This can be achieved by using a GNSS receiver in each piece of measurement equipment, although the accuracy of the GNSS receivers must be taken into account when comparing the two values. For example, if the GNSS receivers each have an accuracy of $\pm x$ ns, the potential error in the measurement is at least $\pm 2x$.

For some of the requirements identified in Table 2 of [ITU-T G.8271], the accuracy of the GNSS receivers will be a significant fraction of the measurement limit. However, given that these requirements always apply to overlapping coverage areas from neighbouring base stations, it might be expected that much of the systematic error (i.e., satellite position, velocity and time error, and ionospheric delay) should be common between the two locations, since they will be reasonably close together. Also, time calibration of both items of measurement equipment (preferably in a location close to the test sites) prior to the test may reduce this time error contribution.

Figure XI.4 shows the measurement method, using tapped monitoring as in Figure III.2. The tapped monitoring method requires temporarily breaking the link between the T-BC and T-TSC, which may not be acceptable for in-service equipment due to the interruption of active traffic. Therefore, in the field it may be more appropriate to use either active probe monitoring or 1 PPS measurement. These are shown in Figures XI.5 and XI.6. If the end application also generates a 1 PPS output for measurement purposes, this could be used instead of the 1pps output of the T-BC.

The figures below do not make any assumptions about the number of T-BCs deployed in the network. In these figures, the dotted line denoted C corresponds to reference point C in Figure 7-1. All cable delays between the T-BC and the measurement equipment, and from the GNSS antenna to the measurement equipment must be carefully measured and compensated for in order to obtain the best accuracy possible. In addition, for PTP connections the delay asymmetry should be measured and compensated for.
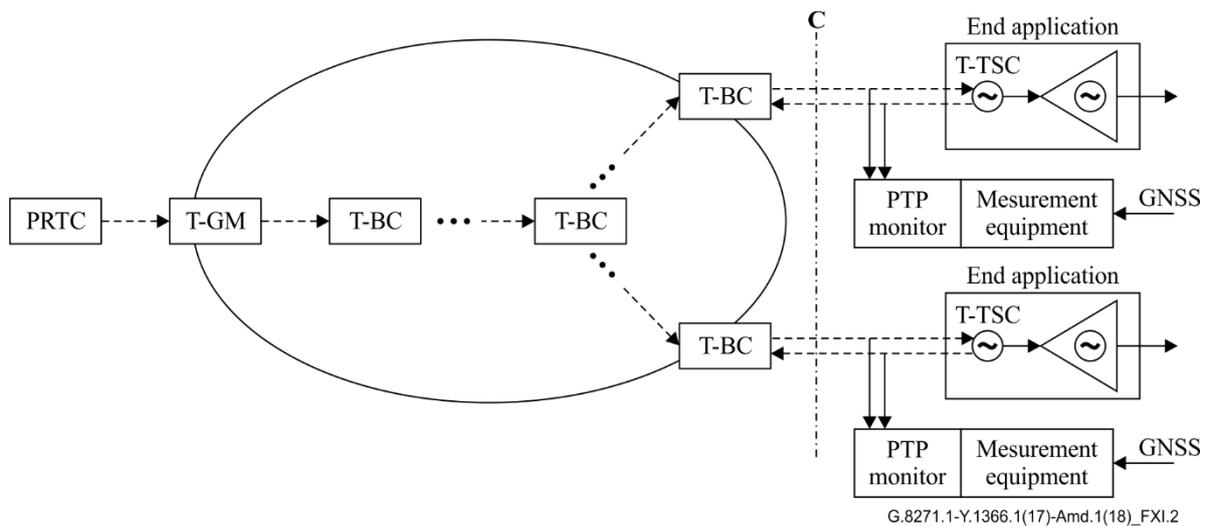

G.8271.1-Y.1366.1(17)-Amd.1(18)_FXI.2

Figure XI.4 – Maximum relative time error measurement in a field environment, with geographically separated measurement points and tapped monitoring

G.8271.1-Y.1366.1(17)-Amd.1(18)_FXI.5

Figure XI.5 – Maximum relative time error measurement in a field environment, with geographically separated measurement points and active monitoring

G.8271.1-Y.1366.1(17)-Amd.1(18)_FXI.6

Figure XI.6 – Maximum relative time error measurement in a field environment, with geographically separated measurement points and 1pps monitoring
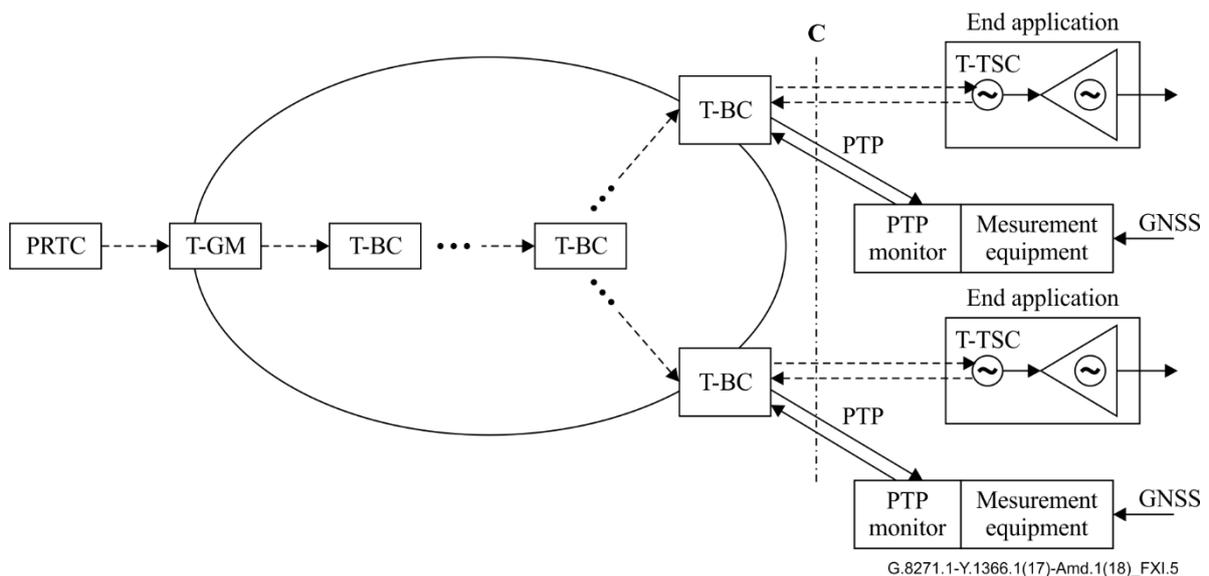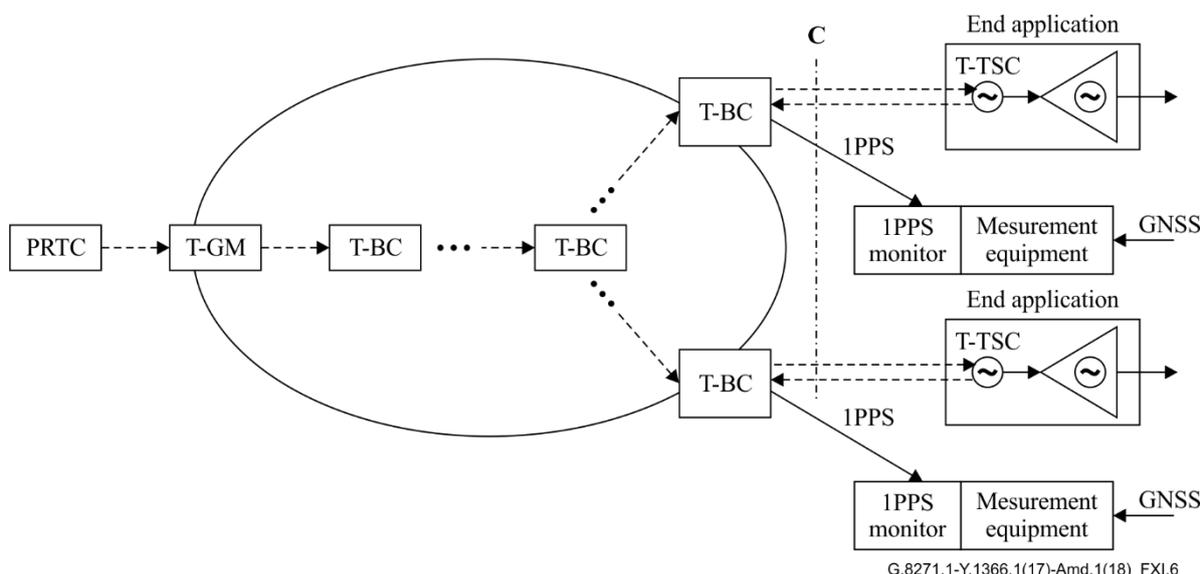
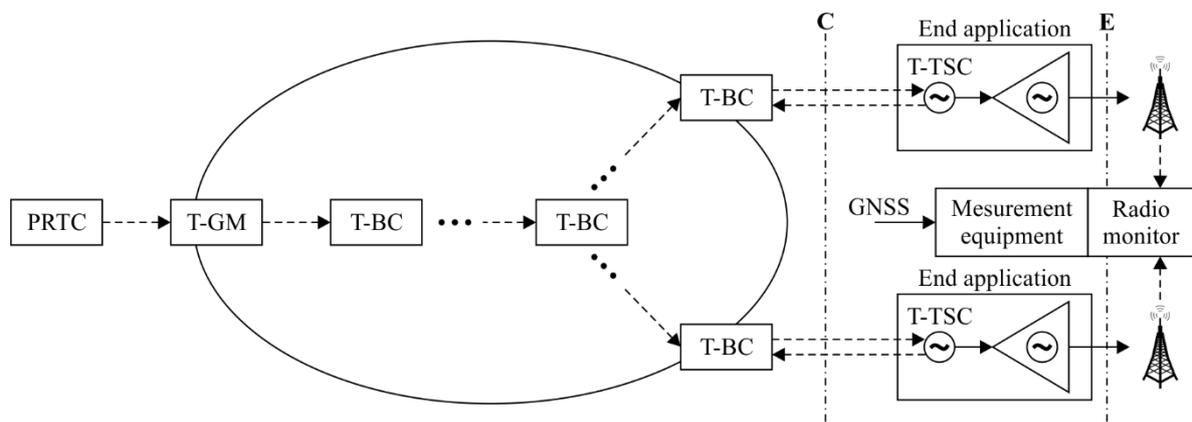### XI.1.3   Measurement in a field environment using radio signals

The alternative to measuring the wireline connection on the backhaul interface is to measure the output of the base station, i.e., the radio signal. While the two base stations are geographically separated, the maximum relative time error requirement applies to the area of overlapping coverage between the two. Therefore, it is possible to measure the time alignment of the radio signals simultaneously at any point within the overlapping coverage area. This allows the measurement to be made by a single piece of measurement equipment with two radio interfaces and a common time reference, removing the error caused by having separate GNSS receivers in each test set.

Figure XI.7 shows the measurement method, using a single piece of measurement equipment monitoring both the radio signals. This is a passive measurement based on observing the phase of the radio frames using methods similar to the radio interface based synchronization (RIBS) described in [b-3GPP TR 36.898]. The measurement equipment is not required to function as a user equipment (UE) in order to make this phase measurement.

It is not strictly necessary for the measurement equipment to be GNSS-referenced, since the radio signals are compared to the same clock within the measurement equipment. However, if the absolute time error of the radio signals to the PRTC is required to be measured, then the measurement equipment must be GNSS referenced.

The mobile radio standards specify the time alignment of the radio signals at the antenna location. Therefore, to correctly calculate the maximum relative time error between the signals, the path delay from each antenna to the measurement equipment must be compensated for. This may be calculated from the positions of the antennas and the measurement equipment, provided these are accurately known, and the signal paths are direct (i.e., not reflected off nearby buildings or geographic features).

As before, the figure does not make any assumptions about the number of T-BCs deployed in the network. In this figure, the dotted line denoted C corresponds to reference point C in Figure 7-1, and the line denoted E corresponds to reference point E in the same diagram.

Figure XI.7 – Maximum relative time error measurement in a field environment, monitoring the time alignment of the radio signals

Bibliography

[b-3GPP TR 36.898]   3GPP TR 36.898 (2016), *Network Assistance for Network Synchronization.*
http://www.3gpp.com/ftp/Specs/html-info/36898.htm

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